WRINKLING AND SPRINGBACK IN
ELECTROMAGNETIC SHEET METAL FORMING AND
ELECTROMAGNETIC RING COMPRESSION

A Thesis
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ABSTRACT

The wrinkling and springback characteristics of aluminum and copper systems in electromagnetic sheet metal forming and electromagnetic ring compression have been studied. Several material and process parameters have been varied and their effects on wrinkling and springback have been documented.

The sheet metal forming experiments were carried using a pancake coil. The effect of energy of forming (on 1100 - O aluminum), thickness of the sheet metal (on 1100 - O aluminum), temper of the metal (by comparing the O temper with the T6 temper), die geometry, stand-off distance and material (by comparing 1100 - O aluminum with Oxygen Free High Conductivity copper) have been analyzed. The springback measurements were made using a Coordinate Measuring Machine (CMM). Wherever possible, formability data has been presented. A few applications and capabilities of the electromagnetic sheet metal forming process have been demonstrated.

The ring compression experiments were carried out using a single turn coil. The effects of energy (on 6061 - O aluminum), ring thickness (on 6061 - O aluminum), ring height (on 6061 - O aluminum), temper of the metal (by comparing 6061 - O with 6061 - T6), the radial compressive strain and material (by comparing 6061 - O with copper) have been analyzed. The clamping force
(between the rings and the mandrels onto which they were compressed) has been used as a measure of springback.

Possible explanations have been suggested for the observed trends, both in sheet metal forming and in ring compression.
To my parents and sister
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INTRODUCTION

The term “forming window” is often used while discussing a metal forming operation. It represents the ranges over which the different parameters can be varied and the forming operation still completed successfully. The main problems that prevent the successful formation of a part are tearing of the material, wrinkling and springback. One of the important factors controlling these three types of failure is the extent of stretch given to the material. A minimum amount of stretch is necessary to eliminate wrinkling and reduce springback to acceptable limits. But, stretching the material beyond a limit could cause it to tear. Thus, the practical “forming window” in a metal forming operation is limited by the necking / tearing problems on the one hand and the wrinkling and shape control problems on the other. In conventional metal forming processes, this “forming window” is often not large. In metals like aluminum, this window is very narrow as tearing is severe and wrinkling and springback are pronounced too. The High Rate Forming techniques make metals more formable by widening the forming window on both sides.

The enhanced formability obtained in the High Rate Processes, termed Hyperplasticity, is a well established fact now. Apart from aluminum alloys, several metals including copper, iron [1], high strength steel, molybdenum, titanium alloys and stainless steel [2] have shown significant improvements
in ductility when deformed at high strain rates. Metals like Beryllium and Columbium [3] have also been successfully formed using these techniques.

The ability of the High Rate Processes to produce parts having very close tolerances has been widely mentioned in the literature. However, there have been only a few studies of springback in High Velocity Forming and none on wrinkling.

The present work aims at a systematic study of wrinkling and springback, both in sheet metal forming and in ring compression using the electromagnetic forming process. An attempt has been made to determine the effect of several material and process parameters on wrinkling and springback. The sheet metal forming studies analyze the effects of the energy of forming, thickness of the sheet metal, temper of the metal, die geometry and stand-off distance for Aluminum systems. The springback and wrinkling characteristics of aluminum have been compared with that of Oxygen Free High Conductivity (OHFC) Cu. Wherever possible, formability data has also been presented.

The ring compression studies document the effect of energy, ring thickness, ring height, temper of the metal and the radial compressive strain for the 6061 Aluminum alloy. The results for aluminum and copper have been compared.

In view of the broad nature of these studies, it has not been possible to analyze the effect of each of these parameters in depth. General trends have
been noted and possible explanations suggested. The author hopes that the results of this study would indicate the direction for more detailed studies on one or more of the parameters governing the process.

However, independent of a fundamental understanding of the reasons for the improved wrinkling and springback behaviour under high rates, the results of this study should be of interest to the industry. In particular, this study is relevant to some of the current problems of the automotive and can-making industry.
CHAPTER 1
LITERATURE REVIEW

1.1 Introduction

The High Velocity Forming Methods have a very peculiar history. They offer certain distinct advantages over conventional metal forming processes. These advantages led to the rapid development of these techniques for about fifteen years. Some of these techniques were even integrated into the production units of several companies. And then, suddenly, research on these processes were just abandoned for no apparent reason. However, several applications of these processes remained in the industry.

The activity in High Rate Forming Techniques over time, as measured by the literature published, has been traced in figure 1.1. A large portion of the work seems to have been done using the explosive forming technique. The literature during this period documents all the advantages of high rate techniques over conventional methods - increase in formability, the ability to obtain very close tolerances due to reduced springback, reduction in wrinkling, the ability to combine forming and assembly operations, reduced tool making costs and many others. Yet, very few systematic studies have gone into identifying and understanding the factors behind these. The bulk of the literature concentrates on applying these techniques to specific problems.
There have been a few studies on springback in high rate sheet forming and none on wrinkling in high velocity sheet forming. Several analytical studies have gone into determining wrinkling in dynamic ring compression, mainly by the engineering mechanics community. However, there have not been many experimental studies on this. Springback in high rate ring compression is another area that is still completely unexplored. In the subsequent pages of this chapter, literature published on these topics has been reviewed. The literature on formability at high rates has already been well reviewed by V. Balanethiram[4] and M. Altynova[5].

\[\text{Figure 1.1: Activity in High Rate Forming over time}^1\]

\[\text{The data is based solely on the publications listed in The Engineering Index}\]
1.2 Springback in Sheet Metal Forming

1.2.1 Fundamentals of Springback in Sheet Bending

The origin of springback lies in the elastic recovery of metals after bending. When a sheet metal is bent, it strains both plastically and elastically. When the deforming forces are removed, the elastic part of the strain is recovered causing a change in the shape of the metal. This process of springback also leaves behind residual stresses in the metal. The most simple case of springback is that of sheets under pure bending moment. An analysis of this case, developed by Hosford and Caddell [6] has been presented here.

![Schematic of a bent sheet metal](image-url)
The bent sheet metal is shown in figure 1.2. Let r be the radius of curvature measured to the mid-plane and z be the distance of any element from the mid-plane. The engineering strain at z can be derived by considering arc lengths, L measured parallel to the x axis. The arc length at the mid-plane, $L_0$, does not change during bending and may be expressed as $L_0 = r\theta$, where $\theta$ is the bend angle. At $z$, the arc length is $L = (r+z)\theta$. Before bending, both lengths were the same. So the engineering strain is $e_x = (L-L_0)/L_0 = z\theta/r\theta = z/r$. The true strain is

$$\varepsilon_x = \ln\left(1 + \frac{z}{r}\right)$$  \hspace{1cm} (1.1)

But, often the strains are small enough and this can be approximated to

$$\varepsilon_x = \frac{z}{r}$$  \hspace{1cm} (1.2)

With sheet material, $w >> t$. So width changes are negligible. Therefore, bending can be considered as approaching a plane strain operation, where $\varepsilon_y = 0$, $\varepsilon_z = -\varepsilon_x$. The value of $\varepsilon_x$ varies linearly from $-t/2r$ at the inside ($z=-t/2$) to zero at the mid-plane ($z=0$) to $+t/2r$ at the outside ($z=t/2$) from equation (1.2) and figure 1.3 (a). Knowing the strain distribution, the internal stress distribution can be found if the slope of the stress-strain curve is known.

Assume a material that is elastic - ideally plastic as shown in figure 1.3 (b). If the tensile yield stress is $Y$, the flow stress in plane strain will be $\sigma_0 = \sqrt{4/3} \ Y$.

The figure 1.3 (c) is a plot of the stress distribution through the sheet. The entire section will be at a stress, $\sigma_x = \pm \sigma_0$, except for an elastic core near the mid-plane, which will shrink as the bend radius decreases. For most bends, this elastic core can be neglected.
Figure 1.3: Strain and stress distribution across sheet thickness. Bending strain (a) varies linearly across the section. For the non-work-hardening stress-strain relation (b), the bending moment causes the stress distribution in (c). Elastic unloading after removal of the loads results in the residual stresses shown in (d) [6]

To calculate the bending moment, $M$ needed to produce this bend, it is assumed that there is no net external force in the $x$ direction ($\Sigma F_x = 0$). However, the initial force, $dF_x$ acting on any incremental element of cross section, $w dz$ is $dF_x = \sigma_x w dz$. The contribution of this element to the bending moment is the product of the force and lever arm, $z$. So $dM = zdF_x = z\sigma_x w dz$.

The total bending moment is found from

$$M = \int_{-t/2}^{t/2} w\sigma_x zdz = 2 \int_0^{t/2} w\sigma_x zdz$$

(1.3)

For the ideally plastic material with a negligible elastic core, $\sigma_x = \sigma_p$, and

$$M = 2w\sigma_p \int_0^{t/2} zdz = w\sigma_p \frac{t^2}{4}$$

(1.4)

The external moment applied by the tools and the internal moment resisting bending must be equal. So equation (1.4) applies to both. When the external moment is released, the internal moment must also vanish. As the material unbends (springsback) elastically, the internal stress distribution results in a zero bending moment. Since the unloading is elastic,

$$\Delta \sigma_x = E' \Delta \varepsilon_x$$

(1.5)
where, because of plane strain, \( E' = E/(1 - v^2) \). The change in strain is given by

\[
\Delta \varepsilon = \frac{z}{r} - \frac{z}{r'}
\]

(1.6)

where \( r' \) is the radius of curvature after springback. This causes a change in the bending moment, \( \Delta M \) of

\[
\Delta M = 2w \int_0^{1/2} \sigma' \Delta z dz = 2w \int_0^{1/2} E' \left( \frac{1}{r} - \frac{1}{r'} \right) z^2 dz
\]

(1.7)

or

\[
\Delta M = \frac{wE't^3}{12} \left( \frac{1}{r} - \frac{1}{r'} \right)
\]

(1.8)

Since \( M - \Delta M = 0 \) after springback, from equations (1.4) and (1.8)

\[
\frac{wE't^3}{12} \left( \frac{1}{r} - \frac{1}{r'} \right) = \frac{w\sigma_0 t^2}{4}
\]

(1.9)

or

\[
\frac{1}{r} - \frac{1}{r'} = \frac{3\sigma_0}{tE'}
\]

(1.10)

The resulting residual stress, \( \sigma' = \sigma - \Delta \sigma = \sigma_0 - E' \Delta \varepsilon = \sigma_0 - E'z(1/r - 1/r') = \sigma_0 - E'z(3\sigma_0/tE') \),

\[
\sigma' = \sigma_0 \left( 1 - \frac{3z}{t} \right)
\]

(1.11)

This is plotted in figure 1.3 (d). Note that on the outside surface where \( z = t/2 \), the residual stress, \( \sigma' \) is compressive and equal to \(-\sigma_0/2\). On the inside surface, where \( z = -t/2 \), \( \sigma' \) is tensile and equal to \(+\sigma_0/2\).

### 1.2.2 Factors Affecting Springback

Several material and process parameters affect springback in conventional forming methods. The material parameters include the yield strength,
ultimate tensile strength, thickness of the sheet and temper of the material. Process parameters include the hold-down force on the sheet, lubrication between the die and the sheet metal and the compressive stress on the sheet metal in the thickness direction. In high rate techniques, in addition to these factors, the energy used to deform the material, the stand-off distance and vacuum level also have an effect on springback.

Since springback is caused by the elastic portion of the strain, any factor that decreases the ratio of elastic to plastic strain reduces springback. In conventional methods, lower material yield strength, higher tensile strength, higher hold-down force on the sheet, absence of lubrication between the die and the sheet metal and higher compressive stresses on the sheet in the thickness direction cause a reduction in springback. The temper of the material indirectly affects springback by altering the yield stress and the ultimate tensile stress. Springback is also found to be less in thicker sheets.

1.2.3 Springback in High Rate Sheet Forming

A very extensive literature search has brought to light only three studies on springback in High Rate Sheet Forming. Two of these studies have been conducted using explosives and one using impulsive hydraulic pressure to form the metal. These have been discussed chronologically.

The first of these studies was by H.G. Baron and R.H. Henn [7] in 1964. Disks of two aluminum alloys, DTD.687 (5.5% Zn Mg Cu) and HS.10 (1% Si Mg) in the fully heat-treated condition were formed into a shallow spheroidal section cavity in a steel die. RDX/TNT charges were used to supply the energy
for forming and water was used as the medium to transmit the shock pulse. A schematic of the die with the sample in position is shown in figure 1.4.

![Figure 1.4: Steel die, holding ring and test piece](image)

The sheet metal was formed into the die cavity by detonating a pre-determined amount of the charge at a fixed stand-off distance. A series of holes was drilled across a diameter of the dish formed. The dish was then placed back into the die and a dial gage fitted with a needle probe was used to measure the distance between the inner (concave) surface of the dish and the die surface at each of these holes. The thickness of the dish at each point was subtracted from these measurements to arrive at the springback values.

Baron and Henn have carried out two sets of experiments: (1) using two stand-off distances - 4 in. and 16 in. - for a 0.047 in. thick DTD.687 sheet (2) using HS.10 sheets of two different thicknesses - 0.034 in. and 0.126 in. - for a
stand-off distance of 4 in. In each set of experiments, the weight of the explosive used was varied from the minimum required for the sheet to completely contact the die to that at which extensive failure of the sheet occurs.

Figure 1.5: Effect of charge weight on the springback of 0.047 in. DTD.687 after forming in water. (a) Stand-off distance 4 in. (b) Stand-off distance 16 in. [7]

The springback values measured from these experiments with DTD.687 are plotted in figure 1.5. Comparison of figures 1.5 (a) and 1.5 (b) shows that the stand-off distance has little effect on springback. At each distance, the smallest charge which produced complete contact between the die and the sheet resulted in a springback of about 0.1 in. at the pole. Increased charge weight reduced the springback, but the maxima in the curves moved away from the
pole. Surface smoothness was found to deteriorate, with the development of faint marks in concentric circles and a small raised dimple was formed at the center. Further increase in charge weight led to the formation of a hole at the center and a concentric ring of cracks about 3 in. in diameter (in the region of maximum springback). A spring-forward effect was also noticed for the largest charges.

![Figure 1.6: Effect of charge weight on the springback of alloy HS.10 after forming in water with a 4 in. stand-off. (a) Sheet 0.034 in. thick. (b) Sheet 0.126 in. thick.](image)

The springback values measured for the experiments with HS.10 are shown in figure 1.6. HS.10 is reported to have shown lesser springback than DTD.687. This could probably be because HS.10 has a lower yield strength than DTD.687. Large charges produced a series of pronounced ripples in the thinner HS.10
alloy and a 2 oz charge gave a remarkable eruption at the center. There were no concentric ripples in the thicker alloy. The spring-forward effect was again observed, being particularly noticeable in the thicker alloy. As can be seen from figures 1.6 (a) and (b), the largest charges of 2 oz caused a large springback again at the center, suggesting the presence of rebound effects.

Baron and Henn attribute the presence of concentric circles in the thicker alloys and ripples in the thinner alloy to the movement of metal towards the center during the deformation process. The progressive thickening of the metal at the center is manifested as concentric circles in the thicker alloys. In the thinner alloys, this movement of the metal towards the pole is said to cause buckling which ends up as ripples. The spring-forward effect is also explained by a large dimple caused due to accumulated metal at the center. Thickness measurements along the diameter of the dishes seem to support the theory of movement of mass towards the pole.

![Figure 1.7: Experimental Set-Up of Behera et. al. [8]](image-url)
In 1977, T. Behera, S. Misra and J. Banerjee [8] used cordtex explosives to form brass and copper blanks into parabolic dies. The figure 1.7 is a schematic of their experimental set-up. Water was used as the medium for transmitting the shock waves. Parabolic reflectors were used to improve the efficiency of energy transfer. They have studied the effect of the following parameters on springback: (1) size of explosive charge (measured by its length in mm), (2) die material, (3) blank holding force, (4) blank thickness, (5) energy transfer medium and (6) the use of a blanket.

![Figure 1.8: Effect of charge on springback [8]](image)

The variation of springback with the size of the explosive charge is shown in figure 1.8. The sheet metal did not fully contact the die for charges of length 25 mm and 37 mm and hence the curves corresponding to these cannot be considered as springback curves. The 50 mm long charge caused complete contact between the die and the sheet and this caused the minimum springback. Subsequent increases in charge lengths progressively increased the springback. This suggests the presence of rebound effects.
The figure 1.9 is a comparison of the springback values obtained using mild steel and wooden dies. The samples formed with the wooden die show lesser springback. This is attributed to the lower coefficient of restitution between the die and the sheet when wooden dies are used. Wood absorbs the kinetic energy of the moving blank more than a metallic die. This again points to the presence of rebound effects.

From the figure 1.10, it can be seen that an increase in blank holding force reduces springback. This is explained by the increased stretching of the sample (since drawing is prevented) which increases the tensile stress on the blank.
This could also cause the neutral axis in the analysis by Hosford and Cadwell to move out of the sample.

![Copper Thickness Graph](image1)
![Brass Thickness Graph](image2)

Figure 1.11: Effect of blank thickness on springback [8]

![Energy Transfer Medium Graph](image3)

Figure 1.12: Effect of energy transfer medium on springback [8]

It can be seen from figure 1.11 that the springback is lesser for thicker samples. The effect of energy transfer medium on springback is shown in figure 1.12.
The springback is lesser with water compared to an air cell. It is suggested that the second shock wave in the water medium opposes the rebound of the sample and that such an effect is not possible for an air medium.

Finally, the effect of plasticine and rubber blankets is shown in figure 1.13. Use of a blanket seems to reduce springback, with a rubber blanket being more effective than a plasticine blanket. Behera et. al. feel that the blank and the blanket behave like a single piece of material of higher thickness which causes a reduced springback.

In 1981, Yamada et. al. [9] published a study on mechanics of springback in high speed sheet forming. They studied the deformation of rectangular titanium plates into a spherical section steel die both at low rates and high rates. In the static case, the plate was pressed between the dies and high velocity forming was done using impulsive hydraulic pressure. The main purpose of their study was to determine the effect of compressive stress in the thickness direction on springback.
Yamada et. al. have used a single parameter to quantify springback in contrast with the previous studies described. If \( r_0 \) is the radius of curvature of the die and \( r \) is the radius of curvature of the deformed plate, then springback is defined as

\[
\frac{1}{r_0} - \frac{1}{r} = 1 - \frac{r_0}{r} 
\]

(1.12)

After the plate is deformed, the coordinates of the die-side surface of the plate were measured at five points (both ends, center point and the mid-points between the center and the ends). The radius of curvature of the entire sample was taken as that defined by the end points and the center point. Three local radii of curvature were defined using the three sets of three adjacent coordinates. The corresponding springback values were calculated.

The high rate experiments were done by impinging a high speed plastic projectile on water, which transmits the shock wave to the sheet metal. The velocity of the projectile was measured using two laser beams. The collision speed of the sheet metal with the die surface was also measured using the electrical pin-contact method. This was done by repeating experiments (which were done with a steel die) using an identical dental stone die. Three electrical contact-pins embedded at the bottom of the dental stone die were used to obtain the velocity measurements.
The figure 1.14 is a plot of the springback for low rate experiments. Springback is found to decrease monotonically with an increase in the punch load. But, for the range of punch loads used, springback does not reduce to zero.

Yamada et. al. feel that the compressive stresses acting along the thickness direction are responsible for reduction in springback with increasing punch load in low rate forming. The additional compressive stress caused by an increased punch load acts to make the stress distribution along the thickness more uniform which reduces the springback.

The shape of the high rate samples after deformation is shown in the figure 1.15. The figure 1.16 is a plot of the springback in the high rate samples. Springback is found to decrease with increasing collision speed and for collision speeds in excess of 66 m/s, springback is found to be negative, i.e. the radius of curvature of the sample is smaller than that of the die. For a collision speed of 47 m/s, the springback is very close to zero. This suggests
that springback could be eliminated or made minimal by using an optimum collision speed.

Figure 1.15: Specimen shape after bending [9]

Figure 1.16: Collision speed dependence of springback [9]

The explanation for reduction in springback with increasing collision speed in high rate forming is based on a comparison with the low rate forming results. The figure 1.17 is a plot of springback as a function of compressive...
stress for both the low rate and high rate experiments. For the low rate experiments, the compressive stress was evaluated by dividing the punch load by the specimen area projected on a plane normal to the direction of load application. For the high speed experiments, the compressive stress was calculated from impedance mismatch using the following equation.

\[
P = \frac{\rho_1 \rho_2 U_1 U_2}{\rho_1 U_1 + \rho_2 U_2} V
\]

(1.13)

where \( P \) is the compressive stress produced, \( V \) is the velocity of the sheet and \( \rho_1 U_1 \) and \( \rho_2 U_2 \) are the shock impedance of the specimen and the die respectively. Since Hugoniot of the material was not available in the low stress region, evaluation was made upon an acoustic approximation.

![Figure 1.17: Compressive stress dependence of springback in static and high speed bending [9]](image_url)

It can be seen from figure 1.17 that the springback variation with compressive stress is very similar for both the high speed and low speed samples. This suggests that the same mechanism controls springback in both cases.
Yamada et. al. further argue that the shock impedance of steel and dental stone and hence the compressive stresses produced in them are very different. Yet, the compressive stress dependence of springback is the same for both materials and this observation is said to confirm that compressive stresses control springback. The author of this thesis refutes the validity of the latter argument. The compressive stress is computed from the collision speed of the sample. Since the impedance value is constant for a material, the compressive stresses for steel and dental stone will obviously show a similar variation with collision speed, even though the exact values may be different. Thus, the compressive stress and springback are two quantities that depend on the collision speed. There is no basis for relating the two by the latter argument put forth by Yamada et. al.

However, the fact that compressive stresses are responsible for reduced springback at low rates and that the variation of springback with compressive stress at high rates is similar to that at low rates suggest that compressive stresses could indeed be the most important factor affecting springback at high rates.

Yamada et. al. have also attributed the final shape of the high rate samples to the process of bending. Using high speed photography, they have captured snapshots showing the shape of the samples at different stages of deformation. The deformation sequence for the low speed and high speed samples is shown in figure 1.18. When the applied pressure is low, the deforming speed of the specimen is also low. Therefore, the plastic bending waves meet at the center of the sample and the sample collides with the die
subsequently. The entire sample has a "V" shape before colliding with the die, as shown in figure 1.18 (a). Samples deforming by this process end up with a positive springback. On the other hand, when the applied pressure is high the deforming speed is also high. Consequently, as shown in figure 1.18 (b), the specimen collides with the die right from the beginning, starting at the ends and moving towards the center. This process of deformation is said to cause a negative springback.

![Figure 1.18: Deformation sequences of a sheet metal subjected to impulsive hydraulic pressure at (a) low rates (b) high rates](image)

Thus, all the three studies seem to indicate that springback goes through a minimum as forming energy or velocity is increased.

1.3 Wrinkling in Sheet Metal Forming

Wrinkling is caused due to the presence of excess material in the die during a forming operation. Consider a sheet being formed into a female die in the shape of a cone section using a punch. Three directions can be imagined.
(a) the direction of motion of the punch - the z direction
(b) the thickness direction of the sheet - the r direction and
(c) the circumferential direction - the θ direction.

As the sheet moves into the die, there is excess material in the θ direction. As the punch moves into the die, the sheet metal both stretches in the direction of punch movement and also draws in. These have opposing effects as far as material in the θ direction is concerned. When the material stretches in the z direction, it causes a contraction of the sheet in the θ direction. The drawing causes more sheet to come into the die and hence increases the amount of material in the θ direction. If the contraction in the θ direction due to stretching in the z direction does not compensate for the excess material brought in by draw-in, then the excess material results as wrinkles in the final component.

In conventional forming, one of the ways of eliminating wrinkling is to increase the extent of stretching and reduce the draw-in. This can be done by applying a hold down pressure on the sheet. The negative aspect of this is that the sheet is forced to stretch to fill the die and might tear if the forming limit is exceeded.

Wrinkling also strongly depends on the "r" value of the material. The "r" value is defined as the ratio of the width strain to the thickness strain when the sheet is stretched along its length, i.e.

\[ r = \frac{\varepsilon_{\text{width}}}{\varepsilon_{\text{thickness}}} \]  

Thus, if the "r" value is high, the width strain is high and the tendency of the material to wrinkle is lesser.
So far, no systematic procedure has been evolved to quantify or predict wrinkling. The solution to wrinkling problems is often to modify the tooling by trial and error till wrinkling is eliminated.

There has been no fundamental study on wrinkling in high rate forming.

1.4 Springback in Ring Compression

The springback in ring compression is important because of its effect on clamping stress. The electromagnetic process is widely used to compress rings or tubes onto other tubes or mandrels, i.e. the forming and the assembly processes are combined. Often, the requirement in such cases is that the ring or tube should hold on to the mandrel tightly. In other words, the clamping stress should be high. A reduced springback indicates an increase in the clamping stress.

The factors affecting springback in axisymmetric compression include the yield strength of the material, ultimate tensile strength of the material, thickness of the ring, height of the ring, temper of the material and energy used to compress the ring.

No literature was found on springback studies in ring compression.

1.5 Wrinkling in Ring Compression

Wrinkling in ring compression is caused by the non-uniform compression of the ring. Unless the reduction is extremely small, it is not possible to
compress a ring uniformly under static conditions [10]. Below a critical wall thickness to diameter ratio, the ring will buckle under the action of external pressure. Using dynamic compression, larger reductions could be obtained before wrinkling occurs.

In dynamic compression, wrinkling is caused mainly due to small differences in the radial velocities of the ring at different points along its circumference. To the knowledge of the author, there have been no experimental studies on the compression of rings or short cylindrical shells. However, there have been several theoretical studies on buckling of rings and short cylindrical shells during dynamic compression [11, 12, 13]. In these studies, the shell is first assumed to deform uniformly and the effect of slight variations in radial velocity around the circumference are investigated. Representing these perturbations as a Fourier series, analysis shows that a particular term becomes amplified and the number of waves in the final buckled shape can be predicted. No attempt has been made to review the theoretical models proposed as these are beyond the scope of this thesis.

There has been one experimental study of wrinkling of long tubes under high rate compression by J.L. Duncan, W. Johnson and J. Miller [10]. The study has compared the effectiveness of different high rate techniques - electrohydraulic forming, explosive forming, explosive gas forming and water hammer technique - in uniformly reducing a thin-walled tube onto a mandrel. The experimental set up is shown in figure 1.19. The tube to be compressed and the mandrel were placed inside a thick steel cylinder. The tube, mandrel and the cylinder were concentric. The tube was sealed at both ends and the space
between the tube and the mandrel was evacuated. The size of the mandrel was varied to obtain different reductions. Separate heads were attached to the tube for the different forming processes. The experiments were conducted on aluminum, mild steel and stainless steel tubes. The tubes were 12 inches long.

Duncan et. al. observed a characteristic pattern in the geometry of the tubes deformed by explosive forming and electrohydraulic forming. In these processes, the intensity of the pressure pulse might be expected to diminish as the wave passes along the length of the tube. The figure 1.20 is a diagrammatic representation of a typical deformed tube. If the energy released was sufficient, a length "A" of the tube closest to the source was compressed uniformly onto the mandrel. Beyond this region "A", there was frequently a length "B" in which the deformed tube had a number of small wrinkles. Following the region of multiple wrinkling, there was a portion of the tube...
"C" in which a single wrinkle appeared as is characteristic of static reduction. Since the length of the tubes did not change, it was assumed that the reduction took place under plane strain conditions.

Figure 1.20: Diagram of a typical formed tube showing the different modes of deformation [10]

The following observations were also made for the tubes formed with the electrohydraulic and explosive forming processes.

1. For the same amount of energy released, the length of tube reduced uniformly, i.e. length "A", decreased rapidly with increasing reduction.
2. For a constant reduction, the length "A" increased approximately linearly with the energy released.
3. The explosive forming process was found to be more efficient than the electrohydraulic process.

Using the water hammer technique, only one aluminum tube was successfully reduced without wrinkles. The reduction possible was also small. When the explosive gas forming method was used, the tube deformed uniformly along the entire length. At low charge pressures, a large wrinkle tended to form on the tube. However, unlike static forming, the remainder of the circumference was not smooth and contained many small amplitude wrinkles. This uniformity in the shape of the deformed tube has been
attributed to the fact that the pressure pulse is uniform along the tube length in this process.

![Figure 1.21: Approximate forms of pressure waves in the different processes [10]](image)

The difference in the effectiveness between the different process has been explained by the differences in the rise time and the intensity of the pressure pulse for the different processes. The approximate forms of the pressure waves in the different processes is shown in figure 1.21. The electrohydraulic, explosive and explosive gas forming processes have a very short rise time and hence the tube could be successfully reduced by these. The rise time for the water hammer technique is very long and hence the inability to reduce the tubes without wrinkling.

Thus, from the studies of Duncan et. al., it could be concluded that the rise time of the pressure pulse and the energy used to compress the ring or tube are main factors in controlling wrinkling. Also, three modes of deformation can be identified depending on the energy - uniform compression, a large number of small wrinkles and one or two large wrinkles.
CHAPTER 2
THE ELECTROMAGNETIC FORMING PROCESS

2.1 Introduction

The electromagnetic forming (EMF) process is one of the more common high rate techniques. The source of energy used to deform the metal is an electrical discharge. This process is primarily used for three forming operations, namely sheet metal forming, tube expansion and tube compression.

![Figure 2.1: Schematic of the Electromagnetic Forming Equipment](image)

2.2 Equipment

The figure 2.1 is a schematic of the electromagnetic forming equipment. The equipment is made up of the following components.
(i) a capacitor bank that stores electrical energy and discharges it across the forming coil in a very short time interval.

(ii) a charging unit that is used to charge the capacitor bank.

(iii) a discharge circuit, which usually consists of a set of large diameter copper busbars.

(iv) a discharge circuit switch

(v) a forming coil, the geometry of which depends upon the forming operation to be performed.

(vi) a conducting workpiece. In the case of a non conducting workpiece, a conducting driver is necessary.

(vii) the die into which the workpiece is to be formed.

(viii) a vacuum system is often necessary to complete a successful forming operation.

Figure 2.2: A flat coil used to form sheet metal [14]
2.3 Types of Forming Coils

Depending upon the forming operation, three types of coils are used.
(i) A flat coil which consists of a metal strip wound spirally in a plane is shown in figure 2.2. Coils of this type are used for forming of sheet metal.
(ii) A helical coil used for tube expansion is shown in figure 2.3. For an expansion operation, the coil is placed inside the tube to be expanded.
(iii) A coil used for ring compression is shown in figure 2.4. This coil is similar in geometry to an expansion coil. However, during the forming operation, the coil is placed surrounding the tube to be compressed.

Sometimes, fields shapers are used to adapt standard coils to specific applications. The purpose of field shapers is to concentrate the magnetic field
at the required points thereby increasing the force on the workpiece at those points.

2.4 Physics of the Electromagnetic Forming Operation

This process utilizes the energy of the magnetic field to deform the metal. For purposes of discussion, let an expansion operation be considered first. The capacitor bank is discharged across the forming coil through the discharge circuit. This causes a rapidly changing current, say $I_1$, to flow through the forming coil. This current has a transient magnetic field associated with it. The transient magnetic field induces a current, say $I_2$, in the workpiece. By Lenz's law, the direction of $I_2$ is such that it opposes the magnetic field that produced it. In other words, $I_2$ is opposite in direction to $I_1$. Lorentz force acts between the two current carrying conductors. Since the currents are opposing, a repulsive force is developed between the coil and the workpiece. When this magnetic pressure exerted by the coil on the workpiece exceeds the yield stress of the workpiece material, the workpiece is thrown away from the coil, i.e. it plastically deforms and expands.

This explanation can now be easily extended to the other two forming operations. In these cases also, due to repulsion between the coil and the workpiece, the workpiece is thrown away from the coil. When the workpiece is placed inside the helical coil, the repulsion causes compression of the workpiece. In the case of sheet metal forming, the sheet metal is placed over the pancake coil. Due to repulsion, the metal is thrown up (away from the coil) and it can be formed into a desired shape by placing a die in its path.
2.5 Process Variables in EMF

2.5.1 Capacitor Bank

The energy storage capacity, \( E \) of a capacitor bank is given by

\[
E = \frac{1}{2} CV^2
\]  

(2.1)

where, \( C \) is the capacitance and \( V \) is the maximum charging voltage. This usually lies between 6 kJ and 20 kJ for units used for forming small components. The largest magnetic forming unit known to exist [15] has a storage capacity of 240 kJ. The large capacity banks have a number of capacitors connected in parallel. The maximum charging voltage for the bank is generally about 10 kV. In the literature, the ranges of capacitance and voltage which have been used are roughly 10 µF to 5000 µF and 2 kV to 20 kV respectively [16]. In excess of about 25 kV, insulation problems assume importance.

2.5.2 Discharge Current Waveform

In most applications, the primary circuit current waveform is a damped harmonic function. Peak values of the current are typically between 10 kA and 200 kA and the frequency varies between 10 kHz and 75 kHz. [16]. The peak value of the current generally becomes unimportant to metal forming after 1.5 to 4 cycles.

2.5.3 Circuit Resistance and Inductance

The primary circuit conductors and the work coil windings are normally made of heavy copper strip with very low steady current resistance. Due to the high frequency of oscillation and the presence of intense magnetic fields,
the current density in the conductors is far from uniform during the
discharge. Typical primary circuit high frequency resistance is 0.01 to 0.1 ohms
and often, this is many times the steady current resistance. The increase in
resistance at high frequencies is due to the effect of skin depth (see
section 2.5.6).

The forming coil contributes the major part of the primary circuit inductance.
The inductance of a coil would typically be of the order of µH.

2.5.4 Workpiece velocity and Strain Rate

The workpiece velocity in a typical electromagnetic forming operation ranges
from 50 m/s to 250 m/s. The strain rates are of the order of 10^3 or 10^4 /s.

2.5.5 Forming Time

In a typical forming operation, the workpiece moves a distance of about 1 cm
before contacting the die. Assuming an average workpiece velocity of
100 m/s, the time taken to form the metal would be about 100 µs. The number
of operations possible per hour is limited by the time required to charge up
the capacitor bank. This varies widely depending on the capacity of the bank
and the charging circuit. The cooling of the forming coils may also be a
consideration in some cases. Typically, a machine can be operated upto 600 -
1200 operations per hour. However a fully automated equipment can reach
upto 12,000 operations per hour [17]
2.5.6 Skin Depth

It represents the depth (or thickness) to which an oscillating magnetic field can penetrate a conductor. This, in turn, limits the depth upto which current is carried by the conductor. For a non-magnetic material, the skin depth, $\delta_m$ is given by

$$\delta_m = \left(\frac{2}{\mu_0 \sigma f}\right)^{1/2}$$  \hspace{1cm} (2.2)

where $\sigma$ is the electrical conductivity of the material, $f$ is the frequency of the oscillating field and $\mu_0$ is the magnetic permeability of free space. As the skin depth increases, the magnetic field losses increase. Hence, a small value for the skin depth is preferred. The skin depth is usually controlled by varying the frequency.

2.6 Advantages of the Electromagnetic Forming Process

The EM forming process has several advantages over conventional forming processes. Some of these advantages are common to all the high rate processes while some are unique to electromagnetic forming. The advantages include

(i) Significant improvement in formability.

(ii) Wrinkling can be reduced and even eliminated.

(iii) Very close tolerances are possible as springback can be made minimal or even completely eliminated.

(iv) Reproduction of surface details is excellent. Hence, this process could be used for surface embossing.

(v) All the above mentioned advantages can be obtained at ambient temperatures without any special material preparation.
The process is highly reproducible as current passed through the forming coils is the only variable to be controlled for a given forming set-up. This is controlled by the amount of energy discharged.

Significant savings in tooling costs as single sided dies are sufficient.

Forming and assembly operations can be combined into a single operation.

Since there is no mechanical contact with the workpiece (as compared to the use of a punch in conventional processes), surface finish can be given to the workpiece before forming.

Since static forces are absent, relatively light structures are often sufficient to support the dies.

High production rates are possible. The step that would essentially control the production rate would be the time taken for the capacitor bank to charge.

It is an environmentally clean process as no lubricants are necessary.

2.7 Disadvantages of the Electromagnetic Forming Process

These include the following.

(i) Only conducting materials can be formed directly. If non-conductors are to be formed, a conducting driver plate must to be used.

(ii) Safety considerations are high due to the high voltages and currents involved.

(iii) With the technology in its current state, very large sheet metal components cannot be formed, mainly due to problems in design of very large coils.
CHAPTER 3
SHEET METAL FORMING STUDIES

3.1 Experimental Set-Up

The figure 3.1 is a schematic of the equipment used for forming sheet metal. It consists of a flat coil above which the sheet metal to be formed is placed. The die was positioned at a pre-determined distance above the sheet metal. The distance between the die and the sheet metal can be varied using a set of spacers. The coil, sheet metal, die and spacers were enclosed in a cylindrical "blast box". The die and the spacers were supported by the top plate of the blast box. The forming coil was mounted on the bottom plate of the blast box. The top plate of the blast box also has two ports - one for attaching a vacuum pump and the other for a vacuum gage. The entire set-up was raised on four stand-offs and placed on a table. The coil leads were connected to the capacitor bank through a set of bus bars. The figure 3.2 is a photograph of the complete set-up.

The blast box was opened by removing the top plate. A hook was fitted into the top plate and a crane was used to move the top plate up and down.
Figure 3.1: Schematic of experimental set-up for sheet metal forming
3.1.1 The Capacitor Bank

The figure 3.3 is a photograph of the capacitor bank used. It is a 7000 Series Maxwell Magneform Machine. It has a maximum energy storage capacity of 48 kJ. It is to be noted here that, when the experiments were conducted, the capacitor bank was believed to have a maximum capacity of 50 kJ and all the energy values presented in this thesis are based on this. The bank consists of a set of eight capacitors connected in parallel, each having a capacitance of 120 µF. For the sheet metal forming experiments in this study, only four of these eight capacitors were used. The bank is charged using a 460 V single phase AC line. The peak line current is 35 A and the average line current is 10 A to 16 A. Within the capacitor bank, peak DC voltages of 10000 volts can be
reached during discharge. The capacitor usually takes a few seconds to charge at maximum energy.

![Figure 3.3: Photograph of the Capacitor Bank](image)

### 3.1.2 Forming Coil

The figure 3.4 is a photograph of the forming coil used. The coil was made using a copper strip 0.3175 cm thick, 2.54 cm wide and 119.38 cm long. The leads, also made of copper, were first soldered onto the ends of the copper strip. The copper strip was then wound into a coil of five turns. The diameter of the coil was 9.8425 cm. G - 10 blocks were placed around the wound coil (on the sides) and the coil was bolted to the G - 10 blocks. This was to prevent the coil from unwinding. A 3.175 mm thick stainless steel plate was placed beneath the G - 10 blocks. There was a gap between the steel plate and the copper strip. During a forming operation, the sheet metal exerts a downward
force on the coil and the stainless steel plate prevents the copper strip from moving down. The space between the copper windings was filled with epoxy (Resin 862 - Shell product) and cured (curing agent used was RSC-2181, also a Shell product). Layers of non-woven kevlar, 0.127 mm thick were placed over the coil and another coating of epoxy was given on top of the kevlar layers. The epoxy and the kevlar layers insulate the copper windings and prevent arcing between the windings and between the copper strip and the steel base plate. During the forming operation, a sheet of mylar was placed between the coil and the sheet metal to prevent arcing between the two. The distance between the copper windings and the sheet metal was about 1.5 mm to 2 mm.

Figure 3.4 : Photograph of the pancake coil used for forming sheet metal
3.1.3 Dies

Two dies were used in the studies. Both were cone sections, one with a 45 degree semi-apex angle and the other with a 30 degree semi-apex angle. The dies were made of 4140 steel. These were rough machined, then heat treated to harden them and then finished. The heat treatment given consisted of the following steps [18].

1. The die was first stress relieved at 760 °C for 20 minutes.

2. Then, it was cooled in an endothermic atmosphere (CO₂ - 0.2%, CO - 20.5%, H₂ - 38.8%, CH₄ - 0.4 % and N₂ - 40.1%) for 30 minutes to below 315.6 °C (600 °F).

3. The die was then reheated to 830 °C, held at that temperature for 1 hour and oil quenched. The die was washed to remove the oil.

4. Finally the die was tempered at 163 °C for 2 hours and air cooled.

5. The threads were masked during the heat treatment to prevent them from getting hardened too much.

6. The final hardness was 58 on the Rockwell scale.

3.1.4 Spacers

Spacers of height 2.54 cm, 1.27 cm, 0.635 cm and 0.3175 cm were used to position the die at a desired height above the sheet metal. The spacers were also made of 4140 steel. However, these were not hardened as they are not directly impacted by the sheet metal.
3.1.5 Blast Box

The blast box consisted of three parts - a short cylindrical steel pipe which formed the walls, a top plate and a bottom plate. The cylindrical pipe was made of 1026 steel. It had an outer diameter of 27.94 cm, wall thickness of 2.54 cm and length of 17.78 cm. The top plate was made of A36 steel. It had 12 bolt holes which could be used to bolt it to the walls. However, during the actual forming operations, this was not necessary as the vacuum was sufficient to hold the top plate tightly to the walls. The bottom plate was made of lexan. This was bolted to the walls using a set of 12 bolts. The coil was mounted on this plate. Viton O - rings (specification H-2374) of inner diameter 23.4315 cm (9.225 in.) and cross-section 0.5334 cm (0.21 in.) were used to seal the vacuum between the wall and the top and bottom plates. The top plate had provisions for attaching a vacuum pump, a vacuum gage and a hook that could be connected to a crane.

3.2 Sample Preparation

Samples of the following materials and thicknesses were used.

1. 1100-O Aluminum of thickness 1.6 mm
2. 1100-O Aluminum of thickness 1.0 mm
3. 6061-T6 Aluminum of thickness 1.28 mm
4. Oxygen Free High Conductivity Copper of thickness 0.8 mm

The samples used were 9.525 cm in diameter. Square plates of side 10.8 cm were sheared from large sheets and these were machined in a lathe to the specified diameter. The circular blanks were then gridded with a pattern of
circles that could be used for determining the strains at different locations on the sample.

3.2.1 Procedure for Grid-Marking the Sheet Metal Samples

A Lectrotech grid-marking unit was used for etching grid patterns on the surface of the sheet. The following steps were followed.

1. The surface of the sheet sample was cleaned with acetone.
2. The electrode / rocker pad was connected to the main unit.
3. The electrode was connected to a scrap metal base plate. An end of the base plate was bent and the electrode was connected to the bent portion of the plate. This was to ensure that the base plate did not pivot at the point the electrode is connected and rock with that point as the fulcrum.
4. The sheet sample was placed on the base plate, with the surface to be gridded facing up.
5. The surface to be gridded was smeared with the electrolyte to be used for etching.
6. The grid was aligned over the sheet surface.
7. A wick pad was placed on top of the grid.
8. The wick pad was soaked with the electrolyte.
9. The system was turned on and the rocker pad was slowly rocked on the wick pad / grid / sheet sample system till a good grid had been marked on the sheet sample. The duration of rocking was determined by trial and error for each material.
10. The sample was then washed in running tap water and dried in air.
3.3 Parameter(s) Used to Represent Formability

As described in the previous section, a circular grid pattern was etched on the sheet surface. As the sheet metal is deformed, the circles are deformed too. The possible ways in which the circles can deform is shown in figure 3.5. If the sheet is stretched in uniaxial tension, the grid circles elongate in one direction and contract in the other. If the sheet deforms under plane strain condition, the circles elongate in one direction and remain unchanged in the perpendicular direction. Under biaxial tension, the circles elongate in both directions, i.e. they become larger circles. Thus comparing the grids before and after elongation gives the stress state under which the sheet had deformed at different points on the sheet surface. The diameter of the grids along the major and minor axes were measured to determine the major and minor strains ($\varepsilon_1$ and $\varepsilon_2$ respectively) at the different points. The major and minor strains are used as a measure of formability.

![Diagram of grid circle deformation](image)

Figure 3.5: Possible types of deformation of the grid circles.

Another parameter used to represent the extent of deformation of the sample is the height of the formed components. This is a good measure of the total strain in the entire sample. Since the height of the sample varies along the circumference, an average value of the height was calculated using the following procedure. The major and minor axes of the sample were located
visually. The heights of the sample at the ends of the major and minor axes were measured using a CMM (refer section 3.5.1 for details on the procedure used to obtain data from the CMM). The average of these four values was taken as the average height of the sample.

3.4 Parameter(s) Used to Represent Wrinkling

The number of wrinkles in the formed components has been taken as a measure of wrinkling. This was manually counted.

3.5 Parameter(s) Used to Represent Springback

The actual gap between the part formed and the die, when the part was fitted back onto the die has been used to represent springback. The data for calculating the springback was obtained using a Sheffield Cordax model RS-30 DCC Coordinate Measuring Machine (CMM). The machine is installed with a Renishaw PH-9A probe. The software used for data acquisition was “Direct Inspect version 1.04”. The profile of the inner surface of the part on vertical plane sections containing the major and minor axes were obtained. This was matched with the profile of the die and springback computed.

3.5.1 Procedure for Obtaining Data from the CMM

The data obtained from the CMM are essentially the x, y and z coordinates of desired points. The figure 3.6 is a photograph of the CMM used. The CMM has a pointed probe and the coordinates of the tip of this probe with respect to the axes of the CMM could be recorded. The figure 3.7 is a schematic of the top
and front views of the part formed. The asymmetry in the part has been exaggerated for clarity.

Figure 3.6: Photograph of the Coordinate Measuring Machine (CMM)

Figure 3.7: Schematic of the cone section part
The procedure used for obtaining profiles of the parts along their major and minor axes is described below.

1. The part was mounted on plasticine and placed on the table of the CMM.
2. Three points (marked "x" in the figure 3.7) were located on the corner of the part, i.e. on the circle where the walls of the part meet its base. A plane was constructed through these points and the XY plane of the CMM was aligned with this plane. The XY plane of the CMM was now aligned with the corner of the part.
3. Three more points were chosen on the corner of the part and a circle was constructed through the points. The origin of the CMM coordinate system was moved to the center of this circle.
4. The major axis of the part was visually located and a point was chosen on it. A line was constructed through this point and the center of the circle (located in step 2). The Y axis of the CMM was aligned with this line. This completed the creation of a convenient set of datum planes.
5. The CMM was then programmed to record the (x,y,z) coordinates of the inner surface of the part along the major axis at intervals of 1 mm. This was done as follows. The probe was first positioned at one end of the major axis (the end where the wall portion of the sample is longer) and a few millimeters above the sample. The probe was moved down till the tip of the probe contacted the surface of the sample. The coordinates of the tip of the probe at this position was read into a data file. The probe was then moved up and advanced 1 mm along the major axis. Again, the probe was
moved down to collect the data point. This was repeated till the other end of the major axis was reached.

6. The profile of the inner surface of the part along the minor axis was obtained using the same procedure as in step 5.

The profile of the die was also obtained using the same procedure outlined above.

3.5.2 Springback Calculation from the CMM Data

![Figure 3.8: Geometric Considerations in Springback Calculation from CMM Data](image)

The figure 3.8 is a schematic of the profiles of the die and the part. For both the part and the die, the corner is assumed to completely lie on the XY plane \((z=0)\). Hence, the springback at the corner is zero by assumption.

Let the springback on the walls be considered first. Let \(P\) be a point on the inner wall of the part and \(D\) be a point on the wall of the die, where \(P\) and \(D\)
lie on a vertical line. The coordinates of P and D are known from the CMM data. The distance PD is the difference between the z coordinates of D and P. Let the sheet metal contact the die at point A and due to rebound, move to point P. It would have moved along the arc AP with the corner of the die as the fulcrum. Thus, the springback is given by the chord length AP. The line, PB is the perpendicular from the point P to the die wall. For small values of AP, AP = BP. Since the length AP cannot be calculated easily from the data available, BP is taken as the springback. From geometric considerations, 

\[ BP = (z(D) - z(P)) \cdot \cos(45) \]

The springback for the base of the part at any point is the difference in z coordinates of the point on the part and the corresponding point on the die.

### 3.6 Tensile Test Data

Tensile tests were done on the sheet metals used in the experiments. The tensile tests were done on an Instron 1362 machine. The gage length of the tensile specimens was 2.54 cm. The width of the specimens in the gage length was 0.508 cm. An extensometer was mounted on the gage length to record the strain. The tensile tests were done at a crosshead speed of \(1.27 \times 10^{-4} \text{ m/s}\). The figures 3.9, 3.10, 3.11 and 3.12 are engineering stress - strain curves calculated from the tensile test data. The table 3.1 is a summary of the 0.2% proof stress, ultimate tensile strength (UTS) and elongation to failure of the materials.
Table 3.1: Summary of tensile test results for materials used in sheet metal studies

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
<th>0.2% Proof Stress (MPa)</th>
<th>0.2% Proof Stress Ave.</th>
<th>UTS (MPa)</th>
<th>UTS Ave.</th>
<th>% Elongation to failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Trial 1</td>
<td>Trial 2</td>
<td>Ave.</td>
<td>Trial 1</td>
<td>Trial 2</td>
</tr>
<tr>
<td>1100-O</td>
<td>1.60</td>
<td>51.0</td>
<td>47.0</td>
<td>49.0</td>
<td>87.8</td>
<td>88.4</td>
</tr>
<tr>
<td>1100-O</td>
<td>1.00</td>
<td>44.0</td>
<td>40.0</td>
<td>42.0</td>
<td>90.5</td>
<td>90.5</td>
</tr>
<tr>
<td>6061-T6</td>
<td>1.28</td>
<td>260.0</td>
<td>253.0</td>
<td>256.5</td>
<td>305.7</td>
<td>305.7</td>
</tr>
<tr>
<td>OHFC Cu</td>
<td>0.80</td>
<td>144.0</td>
<td>144.0</td>
<td>144.0</td>
<td>234.6</td>
<td>235.7</td>
</tr>
</tbody>
</table>
Figure 3.9: Engineering Stress - Strain curves for 1.6 mm thick 1100 - O sheet

Figure 3.10: Engineering Stress - Strain curves for 1.0 mm thick 1100 - O sheet
Figure 3.11: Engineering Stress - Strain curves for 1.28 mm thick 6061-T6 sheet

Figure 3.12: Engineering Stress - Strain curves for 0.8 mm thick OHFC Cu
3.7 Mass of Samples

Throughout this study, the energy used has been normalized with the mass of the samples. The average mass of each type of blank was determined. Ten samples were chosen randomly for each material and their average mass was computed. The table 3.2 is a listing of the mass of the sample set, the average mass and the standard deviation.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Mass of Samples (gms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1100 - O 1.6 mm thick</td>
</tr>
<tr>
<td>1</td>
<td>30.7068</td>
</tr>
<tr>
<td>2</td>
<td>30.9300</td>
</tr>
<tr>
<td>3</td>
<td>30.9343</td>
</tr>
<tr>
<td>4</td>
<td>30.7030</td>
</tr>
<tr>
<td>5</td>
<td>30.9740</td>
</tr>
<tr>
<td>6</td>
<td>30.7311</td>
</tr>
<tr>
<td>7</td>
<td>30.9835</td>
</tr>
<tr>
<td>8</td>
<td>30.7408</td>
</tr>
<tr>
<td>9</td>
<td>30.7784</td>
</tr>
<tr>
<td>10</td>
<td>30.7154</td>
</tr>
<tr>
<td>Average</td>
<td>30.8197</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>0.1197</td>
</tr>
</tbody>
</table>

Table 3.2: Mass of sample set chosen to calculate average mass of metal blanks
3.8 Effect of Energy

3.8.1 Wrinkling

Samples of the 1.6 mm thick 1100 - O sheet were formed using different energies over the 45 degree semi-apex angle cone section die. The lower bound for the energy was that at which, atleast a few points on the metal blank contacted the die on its walls. The distance between the die and the sample was maintained at 3.175 mm. The vacuum level was held at 150 torr.

The table 3.3 is a listing of the Energy / Mass (E/M) value and the number of wrinkles for each energy used. The figure 3.13 is a plot of the number of wrinkles in the formed parts as a function of E/m.

<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E / m (kJ/kg)</th>
<th>No. of wrinkles</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>32.45</td>
<td></td>
<td>no contact with die</td>
</tr>
<tr>
<td>1.25</td>
<td>40.56</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>1.50</td>
<td>48.67</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>1.75</td>
<td>56.78</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2.00</td>
<td>64.89</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2.50</td>
<td>81.12</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>3.50</td>
<td>113.56</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>4.50</td>
<td>146.01</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5.50</td>
<td>178.46</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>6.50</td>
<td>210.90</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.3 : Wrinkling data for 1.6 mm thick 1100 - O Sheet
Figure 3.13: Effect of energy on wrinkling of 1.6 mm thick 1100-0 sheet

3.8.2 Springback

The springback data was obtained for those samples which did not wrinkle. The springback curves along the major axis for the two thicknesses of 1100-0 and for OHFC Cu over a range of energies are shown in figures 3.14, 3.15 and 3.16. The springback curves along the minor axis for the same materials are shown in figures 3.17, 3.18 and 3.19. For the 1.0 mm thick 1100-0, the energy was increased till the sheet failed by tearing. However, the OHFC Cu and 1.6 mm thick 1100-0 did not fail at the maximum energy that could be discharged through the coil without destroying the coil.
Figure 3.14: Effect of Energy on Springback along Major Axis for 1.6 mm thick 1100 - O
Figure 3.15: Effect of Energy on Springback along Major Axis for 1.0 mm thick 1100-O
Figure 3.16: Effect of Energy on Springback along Major Axis for 0.8 mm thick OHFC Cu
Figure 3.17: Effect of Energy on Springback along Minor Axis for 1.6 mm thick 1100 - O
Figure 3.18: Effect of Energy on Springback along Minor Axis for 1.0 mm thick 1100-O
Figure 3.19: Effect of Energy on Springback along Minor Axis for 0.8 mm thick OHFC Cu

Material: OHFC Cu
Thickness: 0.8 mm
3.9 Effect of Sheet Thickness

3.9.1 Wrinkling

The effect of thickness was studied by comparing two thicknesses - 1 mm and 1.6 mm - of the 1100 - O aluminum. The samples were formed over the 45 degree semi-apex angle cone section die. The distance between the metal blank and the die was maintained at 3.175 mm and the vacuum level was maintained at 150 torr.

The energy used for forming, the corresponding E/m value and the number of wrinkles for the 1 mm thick 1100 - O samples are listed in table 3.4. The figure 3.20 is a comparison of the wrinkling curves for the two thicknesses.

3.9.2 Springback

The two thickness were formed at constant E/m values, i.e. the energies used to form the metal blanks were in the proportion of their masses. The springback of such samples were compared. The springback along the major axis for the two thickness at E/m values of 146 kJ/kg and 211 kJ/kg are compared in figures 3.21 and 3.23. The springback along the minor axis for the same E/m values are compared in figures 3.22 and 3.24.
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>No. of Wrinkles</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.625</td>
<td>33.58</td>
<td></td>
<td>no contact with die</td>
</tr>
<tr>
<td>0.75</td>
<td>40.29</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>0.875</td>
<td>47.01</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>1.05</td>
<td>56.41</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>64.47</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>1.35</td>
<td>72.52</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>80.58</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>1.75</td>
<td>94.01</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2.125</td>
<td>114.16</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2.725</td>
<td>146.39</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>3.325</td>
<td>178.63</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>3.925</td>
<td>210.86</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>4.525</td>
<td>243.09</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5.125</td>
<td>275.33</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5.750</td>
<td>308.90</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>6.350</td>
<td>341.14</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>6.950</td>
<td>373.37</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>7.100</td>
<td>381.43</td>
<td>0</td>
<td>tearing</td>
</tr>
</tbody>
</table>

Table 3.4 : Wrinkling data for 1 mm thick 1100 - O sheet
Figure 3.20: Effect of Sheet Thickness on Wrinkling

Figure 3.21: Effect of thickness on springback along major axis for 1100 - O
Figure 3.22: Effect of thickness on springback along minor axis for 1100 - O

Figure 3.23: Effect of thickness on springback along major axis for 1100 - O
3.10 Effect of Material Temper

3.10.1 Wrinkling

The wrinkling characteristics of 6061 - T6 was compared with that of 1100 - O to study the effect of temper. The metal blanks were formed over the 45 degree die. The distance between the metal blank and the die was 3.175 mm and the vacuum was 150 torr. The number of wrinkles in the T6 samples formed at various energies are listed in table 3.5. The figure 3.25 is a plot of the wrinkling curves of the T6 sheets and the O temper sheets of two thicknesses.
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E / m (kJ/kg)</th>
<th>No. of Wrinkles</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.775</td>
<td>32.88</td>
<td></td>
<td>No contact with die</td>
</tr>
<tr>
<td>1.925</td>
<td>81.67</td>
<td></td>
<td>No contact with die</td>
</tr>
<tr>
<td>2.675</td>
<td>113.49</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>3.050</td>
<td>129.40</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>3.250</td>
<td>137.88</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>3.375</td>
<td>143.18</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>3.450</td>
<td>146.37</td>
<td>10</td>
<td>Tearing</td>
</tr>
</tbody>
</table>

Table 3.5: Wrinkling data for 1.28 mm thick 6061 - T6 sheet

![Graph showing the effect of material temper on wrinkling](image)

Figure 3.25: Effect of Material Temper on Wrinkling
3.10.2 Springback

The effect of temper on the springback characteristics could not be determined as the T6 alloy could not be formed without wrinkling. In other words, the samples still had wrinkles when they failed by tearing.

3.11 Effect of Die Geometry

3.11.1 Wrinkling

The 1.6 mm thick 1100 - O aluminum blanks were formed over a 30 degree semi-apex angle cone section die. The results from these experiments were compared with the data for the samples formed over the 45 degree die. The distance between the metal blank and the die was maintained at 3.175 mm and the vacuum level in the experiments was 150 torr.

The number of wrinkles in the samples formed with different energies over the 30 degree die are listed in table 3.6. The wrinkling curves for the samples formed over the two dies are compared in figure 3.26.

3.11.2 Springback

The 1.6 mm thick 1100 - O samples could not be formed over the 30 degree die without wrinkling. Hence, the variation in springback with die geometry could not be studied.
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E / m (kJ/kg)</th>
<th>No. of Wrinkles</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>32.45</td>
<td></td>
<td>No contact with die</td>
</tr>
<tr>
<td>1.50</td>
<td>48.67</td>
<td></td>
<td>No contact with die</td>
</tr>
<tr>
<td>2.00</td>
<td>64.89</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>2.50</td>
<td>81.12</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>3.00</td>
<td>97.34</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>3.25</td>
<td>105.45</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>3.50</td>
<td>113.56</td>
<td>4</td>
<td>Tearing</td>
</tr>
</tbody>
</table>

Table 3.6: Wrinkling data for 1.6 mm thick 1100-0 samples formed over a 30 degree semi-apex angle cone section die.

Figure 3.26: Effect of Die geometry on Wrinkling.
3.12 Effect of Stand-off distance

Samples of the 1.0 mm thick 1100 - O sheet were formed over the 45 degree die at stand-off distances of 0.375 cm, 1.588 cm, 2.858 cm and 4.128 cm. The energy used in the experiments was held constant at 5.125 kJ, which gave a E/m value of 275.33 kJ/kg. The vacuum level was maintained at 150 torr.

The sample formed at 0.375 cm completely took the shape of the die except for a small bubble close to the center of the sample. Wrinkling was absent in this sample. The samples formed at 1.588 cm and 2.858 cm did not wrinkle. The walls of these samples were well formed. However, the base of the sample did not conform to the die. The base protruded in at some points and bulged out at some points. The sample formed at a distance of 4.128 cm showed two wrinkles. The base of this sample also was not formed well.

3.13 Effect of Material

3.13.1 Wrinkling

The wrinkling characteristics of the 1 mm thick 1100 - O was compared with that of 0.8 mm thick OHFC copper. The samples were formed over the 45 degree die. The distance between the metal blank and the die was 3.175 mm and the vacuum was 150 torr.
The wrinkling data for the OHFC Cu samples are listed in table 3.7. The wrinkling curves for the 1100 - O Al and the OHFC Cu are compared in figure 3.27.

### 3.13.2 Springback

The springback of the 1100 - O aluminum and OHFC copper formed at the same E/m values were compared. The springback along major axis for E/m values of 114 kJ/kg and 146 kJ/kg are compared in figures 3.28 and 3.30. The corresponding springback along the minor axis are compared in figures 3.29 and 3.31.

<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E / m (kJ/kg)</th>
<th>No. of Wrinkles</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.000</td>
<td>20.17</td>
<td></td>
<td>no contact with die</td>
</tr>
<tr>
<td>1.250</td>
<td>25.21</td>
<td>19</td>
<td>almost contacted die</td>
</tr>
<tr>
<td>1.600</td>
<td>32.27</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>2.425</td>
<td>48.91</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>3.225</td>
<td>65.04</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>4.025</td>
<td>81.18</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>4.425</td>
<td>89.28</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5.625</td>
<td>113.45</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>7.250</td>
<td>146.22</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>8.050</td>
<td>162.36</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.7: Wrinkling data for 0.8 mm thick OHFC Copper
Figure 3.27: Comparison of wrinkling curves for 1100-O and OHFC Cu

Figure 3.28: Effect of Material on Springback along Major Axis
Figure 3.29: Effect of Material on Springback along Minor Axis

Figure 3.30: Effect of Material on Springback along Major Axis
3.14 Formability Data

Some of the largest strains obtained in the 1.0 mm thick 1100 - O samples are plotted on a conventional (low rate) Forming Limit Diagram (FLD) in the figure 3.32. The strains plotted are "safe" strains, i.e. the sample had not necked or failed at these points. It is to be noted that the strains obtained at high rates are considerably higher than that predicted by the conventional FLD.

The height of the samples formed at different energies has also been determined. This data for the 1.6 mm thick 1100 - O aluminum, 1.0 mm thick 1100 -O aluminum and the 0.8 mm thick OHFC copper are plotted in the figures 3.33, 3.34 and 3.35 respectively.
Figure 3.32 : Strains obtained in the 1.0 mm thick 1100 - O samples at high rate plotted on a conventional FLD (adapted from [19]).

Figure 3.33 : Average Sample Height of the 1.6 mm 1100 - O samples formed at different energies.
Figure 3.34: Average Sample Height of the 1.0 mm thick 1100-O samples formed at different energies.

Figure 3.35: Average Sample Height of the 0.8 mm thick OHFC copper samples formed at different energies.
3.15 Applications

3.15.1 Speaker Diaphragms

The electromagnetic forming process was developed for the commercial production of speaker diaphragms for the AWS Group of Industries, West Virginia. The figure 3.36 is a photograph of the speaker diaphragm formed using EMF. The diaphragm is made of a titanium foil 0.0254 mm thick.

![Figure 3.36: Photograph of a Speaker Diaphragm made using EMF](image)

It is to be noted that the company had earlier tried to form this part by conventional forming processes. However, as the titanium sheet was extremely thin, mechanical contact with the tooling caused tearing in these processes. Further, the application of the component demanded an excellent surface finish and very high dimensional accuracy. These could not be obtained in conventional processes, but was possible using the electromagnetic forming process. Infact, the company made some CMM scans on the parts produced and within the limits of resolution, they
could not detect any difference between the profile of die and the component made.

3.15.2 *Surface embossing*

The figure 3.37 is a photograph of a part that resembles the corner of a car door panel. One of the faces of the corresponding die was polished and a 1100 - O sheet was formed over the die after sticking a triangular piece of grit paper on the polished face. As can be seen from the photograph, the polished surface caused a bright surface on the sheet while the sandpaper provided a dull finish within this bright surface. This demonstrates that very high contact pressures are generated during electromagnetic forming and that the technique could be used for surface embossing. Since there is no mechanical contact of any tooling with the part, the surface finishing operation can be done prior to the forming operation too.

![Figure 3.37: A demonstration of the surface embossing capabilities of the EMF](image)
CHAPTER 4
RING COMPRESSION STUDIES

4.1 Experimental Set-Up

The figure 4.1 is a schematic of the experimental set-up for the ring compression experiments. A single turn compression coil was used for the compression operation. This is a variation of the compression coils discussed in Chapter II. The ring to be compressed was placed inside the circular slot in the coil. The mandrel onto which the ring is to be compressed was placed inside the ring.

Figure 4.1 : Schematic of set-up for ring compression
The mandrel, ring and the circular slot were made concentric using suitable fixtures. The fixtures used also centered the ring vertically with respect to the coil. The ring, mandrel and the fixtures used for alignment were supported by a G-10 base plate. The G-10 base plate was taped tightly to the coil and gap of 8.64 mm was maintained between the coil and the G-10 plate by a lexan spacer placed between them. A layer of mylar was inserted between the ring and the coil to prevent arcing between the two.

The capacitor bank described in section 3.1.1 was used for the ring compression experiments also. All the eight capacitors of the bank were used. When the capacitor bank discharges across the coil, the current takes a path around the slot as shown by the arrows. As explained in Chapter II, this causes the ring to be compressed. If the energy is sufficiently high, the ring compresses onto the mandrel.

4.1.1 Single Turn Coil

The single turn coil was made out of a rectangular 6061-T6 aluminum plate 1.32 cm thick. It consists of a circular slot in the center where the ring to be compressed is placed. It also has a narrow groove running from the slot to the edge of the coil to establish a current path. The coil is bolted onto the busbars, which in turn are connected to the capacitor bank.

4.1.2 Mandrels

Mandrels of three different diameters - 2.54 cm, 3.175 cm and 3.81 cm - were used in the experiments to obtain different radial compressions of the ring. The mandrels were made of 1018 steel in the cold finished condition. The
length of the mandrels ranged from 3.2 cm to 3.45 cm. The end faces of the mandrels were machined in a lathe to make the faces flat and perpendicular to the cylindrical surface.

4.1.3 Fixtures for Alignment

The fixtures used for aligning the ring and the mandrel with the coil had a general shape shown in the figure 4.3. They were annular rings with an inner diameter just larger than the diameter of the mandrel and an outer diameter just smaller than the diameter of the circular slot of the coil. The mandrel was placed inside the slot in the fixture. The ring was placed on the flat surface of the fixture and the height of these fixtures were varied to center the ring vertically along the thickness of the coil. Naturally, a different fixture was used for each ring height / mandrel diameter combination.

Figure 4.3 : A typical fixture used for alignment of ring and mandrel

The fixtures were made of lexan. The flat surfaces of the fixtures were made extremely smooth so that the rings could move freely on them during compression.
4.1.4 Ring Samples

The material, thickness and height of the ring samples studied are listed in table 4.1. All the rings had an outer diameter of 5.08 cm. Long tubes were cut into rings using a lathe.

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Material</th>
<th>Ring Thickness (mm)</th>
<th>Ring Height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>6061-0</td>
<td>1.651</td>
<td>5.08</td>
</tr>
<tr>
<td>2.</td>
<td>6061-0</td>
<td>1.245</td>
<td>5.08</td>
</tr>
<tr>
<td>3.</td>
<td>6061-O</td>
<td>1.651</td>
<td>10.16</td>
</tr>
<tr>
<td>4.</td>
<td>6061-T6</td>
<td>1.651</td>
<td>5.08</td>
</tr>
<tr>
<td>5.</td>
<td>Cu</td>
<td>1.600</td>
<td>5.08</td>
</tr>
</tbody>
</table>

Table 4.1 : List of ring specimens used in Ring Compression Studies

4.2 Parameter(s) Used to Represent Deformation

The strains in the compressed rings vary considerably in all directions. The thickness strain varies along the circumference and height of the ring. The axial strain (strain in the height direction) varies along the circumference and thickness of the ring.

The minimum and maximum true axial strains in the rings were determined to give an estimate of the range in which the axial strains lie. The height of the rings after compression was measured at several points along the circumference and the maximum and minimum of these values were taken to compute the maximum and minimum axial strains. The circumferential
strain in the samples can be computed from the initial and final diameter of the rings. From this data, the range for the true thickness strain can be calculated.

4.3 Parameter(s) Used to Represent Wrinkling

The number of wrinkles in the compressed rings was taken as a measure of wrinkling. This was manually counted.

4.4 Parameter(s) Used to Represent Springback

The force with which the ring clamps onto the mandrel has been used as a rough measure of springback. After a ring was compressed onto a mandrel, the ring was pushed out of the mandrel. The force necessary to push the ring was plotted as a function of displacement. The peak load in the load Vs displacement graph was taken as the clamping force.

The figure 4.4 is a schematic of the set-up for pushing out the rings. The diameters of the sleeves were such that they were just large enough to allow the mandrels to pass through, but too small for the rings to pass through. The mandrels were placed in the sleeves as shown. The sleeve - mandrel combination was pressed between two platons of a Mechanical Testing Machine (model MTS 606). This caused the mandrel to move into the sleeve while the ring remained in position. Thus the ring moved relative to the mandrel.
Let $F_{\text{clamping}}$ be the clamping force of the ring. When the ring tries to move or moves relative to the mandrel, this is opposed by a frictional force between them. While the ring is still stationary relative to the mandrel, the ideal value of the frictional force is given by

$$F_{\text{friction}} = \mu_s F_{\text{clamping}} \quad (4.1)$$

where, $\mu_s$ is the coefficient of static friction between the ring and the mandrel. Once the ring moves relative to the mandrel, the frictional force between them is given by

$$F_{\text{friction}} = \mu_k F_{\text{clamping}} \quad (4.2)$$

where $\mu_k$ is the coefficient of kinetic friction between the ring and the mandrel. It is assumed that the coefficient of friction between the mandrel material and the different ring materials do not vary much. Since the force necessary to push the rings is equal to the frictional force,

$$F_{\text{clamping}} = \text{constant} \times F_{\text{applied}} \quad (4.3)$$
and variation of $F_{\text{applied}}$ with any parameter would be similar to the variation of $F_{\text{clamping}}$.

The analysis above takes into account only the ideal frictional force between the mandrel and the ring. The movement of the ring over the mandrel is resisted by other forces caused by the compression of the mandrel when impacted by the ring and possibly, a local bonding between the ring and the mandrel at high energies. Thus, the measured force is not completely predicted by the friction model.

The load Vs displacement graphs obtained while pushing out the rings had either one peak or two peaks. The figures 4.5 and 4.6 are typical graphs of each case. In either case, the greater of the two values was taken as the clamping force.

![Figure 4.5: Typical Load Vs Displacement graph with one peak](image-url)
Figure 4.6: Typical Load Vs Displacement graph with two peaks

4.5 Tensile Test Data

Tensile tests were done on the ring materials used in the experiments. The tensile tests were done on an Instron 1362 machine. The gage length of the tensile specimens was 2.54 cm. The width of the specimens was 0.508 cm. An extensometer was mounted on the gage length to record the strain. The 0.2% proof stress, ultimate tensile strength (UTS) and elongation to failure of the materials are listed in table 4.2. The figures 4.7, 4.8, 4.9, 4.10, 4.11 and 4.12 are engineering stress-strain curves calculated from the tensile test data.
<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
<th>Direction</th>
<th>0.2% Proof Stress (MPa)</th>
<th>UTS (MPa)</th>
<th>% Elongation to failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Trial 1</td>
<td>Trial 2</td>
<td>Ave.</td>
<td>Trial 1</td>
</tr>
<tr>
<td>6061 - O</td>
<td>1.651</td>
<td>circumferential</td>
<td>57.5</td>
<td>75.0</td>
<td>66.3</td>
</tr>
<tr>
<td>6061 - O</td>
<td>1.651</td>
<td>axial</td>
<td>48.0</td>
<td>53.0</td>
<td>50.5</td>
</tr>
<tr>
<td>6061 - O</td>
<td>1.245</td>
<td>circumferential</td>
<td>67.0</td>
<td>65.0</td>
<td>66.0</td>
</tr>
<tr>
<td>6061 - T6</td>
<td>1.651</td>
<td>circumferential</td>
<td>275.0</td>
<td>262.0</td>
<td>268.5</td>
</tr>
<tr>
<td>6061 - T6</td>
<td>1.651</td>
<td>axial</td>
<td>280.0</td>
<td>236.0</td>
<td>258.0</td>
</tr>
<tr>
<td>Cu</td>
<td>1.600</td>
<td>circumferential</td>
<td>255.0</td>
<td>318.0</td>
<td>286.5</td>
</tr>
<tr>
<td>Cu</td>
<td>1.600</td>
<td>axial</td>
<td>305.0</td>
<td>305.0</td>
<td>305.0</td>
</tr>
</tbody>
</table>

Table 4.2: Summary of tensile test results for materials used in ring compression studies
Figure 4.7: Engineering Stress - Strain curves for 1.651 mm thick 6061 - O tube in the circumferential direction

Figure 4.8: Engineering Stress - Strain curves for 1.651 mm thick 6061 - O tube along the axial direction
Figure 4.9: Engineering Stress - Strain curves for 1.651 mm thick 6061-T6 tube in the circumferential direction.

Figure 4.10: Engineering Stress - Strain curves for 1.651 mm thick 6061-T6 tube along the axial direction.
Figure 4.11: Engineering Stress - Strain curves for 1.6 mm thick Cu tube in the circumferential direction

Figure 4.12: Engineering Stress - Strain curves for 1.6 mm thick Cu tube along the axial direction
4.6 Mass of Ring Samples

As in the sheet metal experiments, the energy used has been normalized with the mass of the samples in the ring compression study too. The average mass of each type of ring was determined using a random sample set of ten rings for each type. The table 4.3 is a listing the mass of the sample set, the average mass and the standard deviation.

4.7 Effect of Energy

4.7.1 Wrinkling

Rings of the 1.651 mm thick 6061-O were compressed using different energies onto a 3.175 cm mandrel. At low energies, the rings did not compress enough to contact the mandrel. As the energy was increased, the ring contacted the mandrel, but moved freely over it. At still higher energies, the ring contacted the mandrel and remained tightly clamped to it. The energy was increased till the rings failed by tearing.

The number of wrinkles in the rings compressed at different energy levels is listed in table 4.4. The number of wrinkles is plotted as a function of E/m in the figure 4.13.

4.7.2 Clamping Force

The peak loads obtained from the load Vs displacement graphs for the rings compressed at different energy levels are listed in table 4.5. The figure 4.14 is a plot of the peak load as a function of E/m.
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Mass of Sample (gms)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6061 - O t = 1.651 mm h = 5.08 mm</td>
</tr>
<tr>
<td>1</td>
<td>3.4722</td>
</tr>
<tr>
<td>2</td>
<td>3.4716</td>
</tr>
<tr>
<td>3</td>
<td>3.4716</td>
</tr>
<tr>
<td>4</td>
<td>3.4683</td>
</tr>
<tr>
<td>5</td>
<td>3.4447</td>
</tr>
<tr>
<td>6</td>
<td>3.4742</td>
</tr>
<tr>
<td>7</td>
<td>3.4656</td>
</tr>
<tr>
<td>8</td>
<td>3.4752</td>
</tr>
<tr>
<td>9</td>
<td>3.5013</td>
</tr>
<tr>
<td>10</td>
<td>3.4724</td>
</tr>
<tr>
<td>Average</td>
<td>3.4717</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0.0136</td>
</tr>
</tbody>
</table>

Table 4.3: Mass of sample set chosen to calculate average mass of rings
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>No. of Wrinkles</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>576.09</td>
<td>10</td>
<td>$d_{\text{ring}} &gt; d_{\text{mandrel}}$</td>
</tr>
<tr>
<td>3</td>
<td>864.13</td>
<td>11</td>
<td>ring clamped tightly</td>
</tr>
<tr>
<td>4</td>
<td>1152.17</td>
<td>5</td>
<td>$d_{\text{ring}} &lt; d_{\text{mandrel}}$, but did not clamp tightly</td>
</tr>
<tr>
<td>5</td>
<td>1440.22</td>
<td>1</td>
<td>$d_{\text{ring}} &lt; d_{\text{mandrel}}$, but did not clamp tightly</td>
</tr>
<tr>
<td>6</td>
<td>1728.26</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2016.30</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>2592.39</td>
<td>0</td>
<td>initiation of crack</td>
</tr>
<tr>
<td>10</td>
<td>2880.43</td>
<td>0</td>
<td>failure</td>
</tr>
<tr>
<td>11</td>
<td>3168.48</td>
<td>0</td>
<td>failure</td>
</tr>
</tbody>
</table>

Table 4.4: Wrinkling data for 1.651 mm thick and 5.08 mm high 6061-0 rings

![Effect of Energy on Wrinkling of Rings](image)

Figure 4.13: Effect of Energy on Wrinkling of Rings
<table>
<thead>
<tr>
<th>Energy</th>
<th>E/m</th>
<th>Peak Load 1</th>
<th>Peak Load 2</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kJ)</td>
<td>(kJ/kg)</td>
<td>(kg)</td>
<td>(kg)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>576.09</td>
<td>0.00</td>
<td></td>
<td>d&lt;sub&gt;ring&lt;/sub&gt; &gt; d&lt;sub&gt;mandrel&lt;/sub&gt;</td>
</tr>
<tr>
<td>3</td>
<td>864.13</td>
<td>2.22</td>
<td></td>
<td>ring clamped tightly</td>
</tr>
<tr>
<td>4</td>
<td>1152.17</td>
<td></td>
<td></td>
<td>d&lt;sub&gt;ring&lt;/sub&gt; &lt; d&lt;sub&gt;mandrel&lt;/sub&gt;, but did not clamp tightly</td>
</tr>
<tr>
<td>5</td>
<td>1440.22</td>
<td></td>
<td></td>
<td>d&lt;sub&gt;ring&lt;/sub&gt; &lt; d&lt;sub&gt;mandrel&lt;/sub&gt;, but did not clamp tightly</td>
</tr>
<tr>
<td>6</td>
<td>1728.26</td>
<td>66.51</td>
<td>62.07</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2016.30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>2592.39</td>
<td>509.89</td>
<td></td>
<td>initiation of crack</td>
</tr>
<tr>
<td>10</td>
<td>2880.43</td>
<td>312.58</td>
<td>281.54</td>
<td>failure</td>
</tr>
<tr>
<td>11</td>
<td>3168.48</td>
<td></td>
<td></td>
<td>failure</td>
</tr>
</tbody>
</table>

Table 4.5: Clamping force data for 1.651 mm thick 6061 - O rings of height 5.08 mm
4.7.3 Axial Strain

The table 4.6 lists the minimum and maximum ring heights after deformation and the corresponding true axial strains, $\varepsilon_{\text{axial}}$ for the different energies. The figure 4.15 is a plot of the true strain data as a function of $E/m$. The axial strains were measured only for those samples that did not fail by tearing.
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>Min. Height (mm)</th>
<th>Min. $\varepsilon_{\text{axial}}$</th>
<th>Max. Height (mm)</th>
<th>Max. $\varepsilon_{\text{axial}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>576.09</td>
<td>5.334</td>
<td>0.0488</td>
<td>5.6388</td>
<td>0.1044</td>
</tr>
<tr>
<td>3</td>
<td>864.13</td>
<td>5.588</td>
<td>0.0953</td>
<td>5.9436</td>
<td>0.1570</td>
</tr>
<tr>
<td>4</td>
<td>1152.17</td>
<td>5.893</td>
<td>0.1484</td>
<td>6.3246</td>
<td>0.2191</td>
</tr>
<tr>
<td>5</td>
<td>1440.22</td>
<td>5.817</td>
<td>0.1354</td>
<td>6.9596</td>
<td>0.3148</td>
</tr>
<tr>
<td>6</td>
<td>1728.26</td>
<td>5.842</td>
<td>0.1398</td>
<td>7.7724</td>
<td>0.4253</td>
</tr>
<tr>
<td>7</td>
<td>2016.30</td>
<td>5.867</td>
<td>0.1441</td>
<td>8.4836</td>
<td>0.5128</td>
</tr>
<tr>
<td>9</td>
<td>2592.39</td>
<td>6.375</td>
<td>0.2271</td>
<td>10.5156</td>
<td>0.7275</td>
</tr>
</tbody>
</table>

Table 4.6: Axial Strains for 1.651 mm thick and 5.08 mm high 6061 - 0 Rings

Figure 4.15: Effect of Energy on Minimum and Maximum Axial True Strain
4.8 Effect of Ring Thickness

4.8.1 Wrinkling

The wrinkling characteristics of rings of 6061 - 0 of thicknesses 1.651 mm and 1.245 mm were compared. The ring height was kept constant at 5.08 mm. The rings were compressed onto a 3.175 cm diameter mandrel. The number of wrinkles in the 1.245 mm thick samples formed at different energies are listed in table 4.7. The figure 4.16 is a plot of the wrinkling data as a function of E/m.

<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>No. of Wrinkles</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.55</td>
<td>582.53</td>
<td>12</td>
<td>d_{ring} &gt; d_{mandrel}</td>
</tr>
<tr>
<td>2.30</td>
<td>864.40</td>
<td>12</td>
<td>d_{ring} = d_{mandrel}, but did not clamp tightly</td>
</tr>
<tr>
<td>3.05</td>
<td>1146.27</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>4.60</td>
<td>1728.80</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>5.35</td>
<td>2010.67</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>6.15</td>
<td>2311.33</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>8.45</td>
<td>3175.74</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>9.20</td>
<td>3457.61</td>
<td>0</td>
<td>crack initiation</td>
</tr>
<tr>
<td>9.95</td>
<td>3739.48</td>
<td>0</td>
<td>failure</td>
</tr>
</tbody>
</table>

Table 4.7: Wrinkling Data for 1.245 mm thick 6061 - 0 rings of height 5.08 mm

100
4.8.2 Clamping Force

The peak loads required to move the 1.245 mm thick 6061 - O rings off the mandrel are listed in table 4.8. The same data is plotted as a function of E/m in figure 4.17.

4.8.3 Axial True Strain

The minimum and maximum height of the rings and the corresponding axial true strain values for the 1.245 mm thick 6061 - O rings compressed with different energies are listed in table 4.9. The data is plotted in figure 4.18 as a function of E/m.
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>Peak Load 1 (kg)</th>
<th>Peak Load 2 (kg)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.55</td>
<td>582.53</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.30</td>
<td>864.40</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.05</td>
<td>1146.27</td>
<td>8.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.60</td>
<td>1728.80</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.35</td>
<td>2010.67</td>
<td></td>
<td>64.29</td>
<td></td>
</tr>
<tr>
<td>6.15</td>
<td>2311.33</td>
<td>117.50</td>
<td>93.11</td>
<td></td>
</tr>
<tr>
<td>8.45</td>
<td>3175.74</td>
<td>184.00</td>
<td>208.39</td>
<td></td>
</tr>
<tr>
<td>9.20</td>
<td>3457.61</td>
<td>281.54</td>
<td></td>
<td>crack initiation</td>
</tr>
<tr>
<td>9.95</td>
<td>3739.48</td>
<td></td>
<td></td>
<td>failure</td>
</tr>
</tbody>
</table>

Table 4.8: Clamping Force Data for 1.245 mm thick 6061-O rings of height 5.08 mm
Figure 4.17: Effect of Ring Thickness on Clamping Force

Figure 4.18: Effect of Ring Thickness on Axial True Strain
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>Min. Height (mm)</th>
<th>Min. ( \varepsilon_{\text{axial}} )</th>
<th>Max. Height (mm)</th>
<th>Max. ( \varepsilon_{\text{axial}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.55</td>
<td>582.53</td>
<td>5.3086</td>
<td>0.0440</td>
<td>5.7150</td>
<td>0.1178</td>
</tr>
<tr>
<td>2.30</td>
<td>864.40</td>
<td>5.3594</td>
<td>0.0535</td>
<td>6.0198</td>
<td>0.1697</td>
</tr>
<tr>
<td>3.05</td>
<td>1146.27</td>
<td>5.4102</td>
<td>0.0630</td>
<td>6.1468</td>
<td>0.1906</td>
</tr>
<tr>
<td>4.60</td>
<td>1728.80</td>
<td>5.9182</td>
<td>0.1527</td>
<td>7.2644</td>
<td>0.3577</td>
</tr>
<tr>
<td>5.35</td>
<td>2010.67</td>
<td>5.7912</td>
<td>0.1310</td>
<td>7.3406</td>
<td>0.3681</td>
</tr>
<tr>
<td>6.15</td>
<td>2311.33</td>
<td>5.7658</td>
<td>0.1266</td>
<td>8.1280</td>
<td>0.4700</td>
</tr>
<tr>
<td>8.45</td>
<td>3175.74</td>
<td>5.8674</td>
<td>0.1441</td>
<td>9.6012</td>
<td>0.6366</td>
</tr>
<tr>
<td>9.20</td>
<td>3457.61</td>
<td>6.1976</td>
<td>0.1989</td>
<td>10.7950</td>
<td>0.7538</td>
</tr>
</tbody>
</table>

Table 4.9: Axial True Strain Data for 1.245 mm thick 6061-0 rings

4.9 Effect of Ring Height

4.9.1 Wrinkling

Rings of heights 5.08 mm and 10.16 mm were made from the 1.651 mm thick 6061-0 tube. These were compressed onto a 3.175 cm mandrel using different energies. The number of wrinkles in the rings of height 10.16 mm are listed in table 4.10. The wrinkling curves for the two heights are compared in the figure 4.19.
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>No. of Wrinkles</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.00</td>
<td>574.55</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>6.00</td>
<td>861.82</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>8.00</td>
<td>1149.10</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>10.05</td>
<td>1443.55</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>12.05</td>
<td>1730.82</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>13.00</td>
<td>1867.28</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>14.05</td>
<td>2018.10</td>
<td>0</td>
<td>failure</td>
</tr>
</tbody>
</table>

Table 4.10: Wrinkling Data for 1.651 mm thick 6061 - O rings of height 10.16 mm

Figure 4.19: Effect of Ring Height on Wrinkling
4.9.2 Clamping Force

The peak loads recorded while moving the 6061 - O rings of height 10.18 mm off the mandrel are listed in table 4.11. For some of these rings, three peaks were observed. The figure 4.20 compares the clamping force data for the two heights.

4.9.3 Axial True Strain

The minimum and maximum height of the 6061 rings of initial height 10.16 mm and the corresponding true strains are listed in table 4.12. The figure 4.21 is a comparison of the true strains for the two heights.

![Figure 4.20: Effect of Ring Height on Clamping Force](image)

Figure 4.20 : Effect of Ring Height on Clamping Force
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>Peak Load 1 (kg)</th>
<th>Peak Load 2 (kg)</th>
<th>Peak Load 3 (kg)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.00</td>
<td>574.55</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.00</td>
<td>861.82</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.00</td>
<td>1149.10</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.05</td>
<td>1443.55</td>
<td>117.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.05</td>
<td>1730.82</td>
<td>137.44</td>
<td>230.55</td>
<td>219.47</td>
<td></td>
</tr>
<tr>
<td>13.00</td>
<td>1867.28</td>
<td>95.33</td>
<td>248.29</td>
<td>226.12</td>
<td></td>
</tr>
<tr>
<td>14.05</td>
<td>2018.10</td>
<td></td>
<td></td>
<td></td>
<td>failure</td>
</tr>
</tbody>
</table>

Table 4.11: Clamping Force Data for 1.651 mm thick 6061 - O rings of height 10.16 mm
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>Min. Height (mm)</th>
<th>Min. $\varepsilon_{\text{axial}}$</th>
<th>Max. Height (mm)</th>
<th>Max. $\varepsilon_{\text{axial}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.00</td>
<td>574.55</td>
<td>10.7442</td>
<td>0.0559</td>
<td>11.3538</td>
<td>0.1111</td>
</tr>
<tr>
<td>6.00</td>
<td>861.82</td>
<td>10.8966</td>
<td>0.0700</td>
<td>12.1920</td>
<td>0.1823</td>
</tr>
<tr>
<td>8.00</td>
<td>1149.10</td>
<td>10.8458</td>
<td>0.0653</td>
<td>12.6746</td>
<td>0.2211</td>
</tr>
<tr>
<td>10.05</td>
<td>1443.55</td>
<td>10.8204</td>
<td>0.0630</td>
<td>13.6652</td>
<td>0.2964</td>
</tr>
<tr>
<td>12.05</td>
<td>1730.82</td>
<td>11.0744</td>
<td>0.0862</td>
<td>14.4780</td>
<td>0.3542</td>
</tr>
<tr>
<td>13.00</td>
<td>1867.28</td>
<td>11.2268</td>
<td>0.0998</td>
<td>14.7066</td>
<td>0.3698</td>
</tr>
<tr>
<td>14.05</td>
<td>2018.10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.12: Axial True Strain Data for 1.651 mm thick 6061-O Rings of Height 10.16 mm

![Figure 4.21: Effect of Ring Height on Axial True Strain](image)

Material: 6061-O
Ring Thickness = 1.651 mm

Energy / Mass (kJ/kg)

Figure 4.21: Effect of Ring Height on Axial True Strain
4.10 Effect of Temper

4.10.1 Wrinkling

The effect of temper was studied by comparing the 6061 - O rings with the 6061-T6 rings. The ring height was 5.08 mm and the ring thickness was 1.651 mm. The rings were compressed onto a 3.175 cm mandrel. The wrinkling data for the 6061 - T6 rings is listed in table 4.14. The wrinkling curves for the O temper and the T6 temper are compared in the figure 4.22.

<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>No. of Wrinkles</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.05</td>
<td>865.22</td>
<td>8</td>
<td>(d_{ring} &gt; d_{mandrel})</td>
</tr>
<tr>
<td>5.10</td>
<td>1446.77</td>
<td>9</td>
<td>(d_{ring} &gt; d_{mandrel})</td>
</tr>
<tr>
<td>6.10</td>
<td>1730.45</td>
<td>11</td>
<td>(d_{ring} &lt; d_{mandrel}) but did not clamp tightly</td>
</tr>
<tr>
<td>7.10</td>
<td>2014.13</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>8.10</td>
<td>2297.81</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>9.15</td>
<td>2595.67</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>11.15</td>
<td>3163.03</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>12.20</td>
<td>3460.89</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>13.20</td>
<td>3744.57</td>
<td>2</td>
<td>failure</td>
</tr>
</tbody>
</table>

Table 4.14: Wrinkling Data for 6061 - O Rings
4.10.2 Clamping Force

The peak loads observed while moving the 6060-T6 rings off the mandrel are listed in the table 4.15. The data for the T6 and O temper are compared in the figure 4.23.
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>Peak Load 1 (kg)</th>
<th>Peak Load 2 (kg)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.05</td>
<td>865.22</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.10</td>
<td>1446.77</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.10</td>
<td>1730.45</td>
<td>0.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.10</td>
<td>2014.13</td>
<td></td>
<td>8.88</td>
<td></td>
</tr>
<tr>
<td>8.10</td>
<td>2297.81</td>
<td></td>
<td>33.25</td>
<td></td>
</tr>
<tr>
<td>9.15</td>
<td>2595.67</td>
<td></td>
<td>37.69</td>
<td></td>
</tr>
<tr>
<td>11.15</td>
<td>3163.03</td>
<td>22.17</td>
<td>66.51</td>
<td></td>
</tr>
<tr>
<td>12.20</td>
<td>3460.89</td>
<td>223.90</td>
<td>314.70</td>
<td></td>
</tr>
<tr>
<td>13.20</td>
<td>3744.57</td>
<td></td>
<td></td>
<td>failure</td>
</tr>
</tbody>
</table>

Table 4.15: Clamping Force Data for 6061 - T6 Rings
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>Min. Height (mm)</th>
<th>Min. $\varepsilon_{axial}$</th>
<th>Max. Height (mm)</th>
<th>Max. $\varepsilon_{axial}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.05</td>
<td>865.22</td>
<td>5.2832</td>
<td>0.0392</td>
<td>5.5626</td>
<td>0.0908</td>
</tr>
<tr>
<td>5.10</td>
<td>1446.77</td>
<td>5.3848</td>
<td>0.0583</td>
<td>6.3754</td>
<td>0.2271</td>
</tr>
<tr>
<td>6.10</td>
<td>1730.45</td>
<td>5.4102</td>
<td>0.0630</td>
<td>6.4770</td>
<td>0.2429</td>
</tr>
<tr>
<td>7.10</td>
<td>2014.13</td>
<td>5.4864</td>
<td>0.0770</td>
<td>6.6548</td>
<td>0.2700</td>
</tr>
<tr>
<td>8.10</td>
<td>2297.81</td>
<td>5.4610</td>
<td>0.0723</td>
<td>6.9850</td>
<td>0.3185</td>
</tr>
<tr>
<td>9.15</td>
<td>2595.67</td>
<td>5.5372</td>
<td>0.0862</td>
<td>7.5692</td>
<td>0.3988</td>
</tr>
<tr>
<td>11.15</td>
<td>3163.03</td>
<td>5.6896</td>
<td>0.1133</td>
<td>8.3820</td>
<td>0.5008</td>
</tr>
<tr>
<td>12.20</td>
<td>3460.89</td>
<td>5.8420</td>
<td>0.1398</td>
<td>8.6360</td>
<td>0.5306</td>
</tr>
<tr>
<td>13.20</td>
<td>3744.57</td>
<td>5.9182</td>
<td>0.1527</td>
<td>9.1440</td>
<td>0.5878</td>
</tr>
</tbody>
</table>

Table 4.16: Axial True Strain Data for 6061 - T6 Rings

![Figure 4.24: Effect of Temper on Axial True Strain](image)
4.10.3 Axial True Strain

The true strain data for the 6061 - T6 rings is listed in table 4.16. The true strains observed in the 6061 - O and 6061 - T6 rings are compared in figure 4.24.

4.11 Effect of Radial Strain

4.11.1 Wrinkling

The 1.651 mm thick rings of 6061 - O with a height of 5.08 mm were compressed onto mandrels of three different diameters - 2.54 cm, 3.175 cm and 3.81 cm. The wrinkling data for the rings compressed onto 2.54 cm diameter mandrels are listed in table 4.17. The wrinkling data for the rings compressed onto 3.81 cm diameter mandrels are listed in table 4.18. The figure 4.25 compares the wrinkling curves for the different radial strains.

![Figure 4.25: Effect of Radial Strain on Wrinkling](image)

Material: 6061-O
Ring Thickness: 1.651 mm
Ring Height: 5.08 mm
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>No. of Wrinkles</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1152.17</td>
<td>12</td>
<td>$d_{\text{ring}} &gt; d_{\text{mandrel}}$</td>
</tr>
<tr>
<td>5</td>
<td>1440.22</td>
<td>10</td>
<td>$d_{\text{ring}} &gt; d_{\text{mandrel}}$</td>
</tr>
<tr>
<td>6</td>
<td>1728.26</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2016.30</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2304.35</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>2592.39</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>3168.48</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>3744.56</td>
<td>0</td>
<td>initiation of crack</td>
</tr>
<tr>
<td>15</td>
<td>4320.65</td>
<td>0</td>
<td>failure</td>
</tr>
</tbody>
</table>

Table 4.17: Wrinkling Data for 6061 - O Rings Compressed onto 2.54 cm mandrels
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>No. of Wrinkles</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>576.09</td>
<td>8</td>
<td>(d_{\text{ring}} &gt; d_{\text{mandrel}})</td>
</tr>
<tr>
<td>3</td>
<td>864.13</td>
<td>0</td>
<td>(d_{\text{ring}} &gt; d_{\text{mandrel}})</td>
</tr>
<tr>
<td>4</td>
<td>1152.17</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1440.22</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1728.26</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2016.30</td>
<td>0</td>
<td>crack initiation</td>
</tr>
<tr>
<td>9</td>
<td>2592.39</td>
<td>0</td>
<td>failure</td>
</tr>
</tbody>
</table>

Table 4.18: Wrinkling Data for 6061 - O Rings Compressed onto 3.81 cm mandrels

4.11.2 Clamping Force

The clamping force data for the rings compressed onto 2.54 cm mandrels is listed in table 4.19. The same data for the rings compressed onto 3.81 cm mandrels is listed in table 4.20. The clamping force obtained with the different radials strains are compared in the figure 4.26.
\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Energy (kJ) & E/m (kJ/kg) & Peak Load 1 (kg) & Peak Load 2 (kg) & Comments \\
\hline
4 & 1152.17 & 0.000 & & $d_{\text{ring}} > d_{\text{mandrel}}$ \\
5 & 1440.22 & 0.000 & & $d_{\text{ring}} > d_{\text{mandrel}}$ \\
6 & 1728.26 & 42.120 & & \\
7 & 2016.30 & 121.926 & 128.577 & \\
8 & 2304.35 & 425.639 & & \\
9 & 2592.39 & 558.647 & & \\
11 & 3168.48 & 948.815 & & \\
13 & 3744.56 & 1061.81 & & \text{initiation of crack} \\
15 & 4320.65 & & & \text{failure} \\
\hline
\end{tabular}
\caption{Clamping Force Data for 6061 - O Rings Compressed onto 2.54 cm Diameter Mandrels}
\end{table}
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>$\frac{E}{m}$ (kJ/kg)</th>
<th>Peak Load 1 (kg)</th>
<th>Peak Load 2 (kg)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>576.09</td>
<td>0.00</td>
<td></td>
<td>$d_{\text{ring}} &gt; d_{\text{mandrel}}$</td>
</tr>
<tr>
<td>3</td>
<td>864.13</td>
<td>0.00</td>
<td></td>
<td>$d_{\text{ring}} &gt; d_{\text{mandrel}}$</td>
</tr>
<tr>
<td>4</td>
<td>1152.17</td>
<td>15.52</td>
<td>17.735</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1440.22</td>
<td>33.25</td>
<td>35.470</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1728.26</td>
<td>39.90</td>
<td>70.942</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2016.30</td>
<td>106.41</td>
<td></td>
<td>crack initiation</td>
</tr>
<tr>
<td>9</td>
<td>2592.39</td>
<td></td>
<td></td>
<td>failure</td>
</tr>
</tbody>
</table>

Table 4.20: Clamping Force Data for 6061-0 Rings Compressed onto 3.81 cm diameter Mandrels

![Figure 4.26: Effect of Radial Strain on Clamping Force](image)

Figure 4.26: Effect of Radial Strain on Clamping Force
4.11.3 Axial True Strain

The axial true strain data for the 6061 - O rings compressed onto 2.54 cm diameter mandrels is listed in table 4.21. The true strain data for the rings compressed onto 3.81 diameter mandrels is listed in table 4.22. The figure 4.27 compares the axial strains obtained when the rings were compressed to different radial strains.

<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>Min. Height (mm)</th>
<th>Min. $\varepsilon_{\text{axial}}$</th>
<th>Max. Height (mm)</th>
<th>Max. $\varepsilon_{\text{axial}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1152.17</td>
<td>5.6896</td>
<td>0.1133</td>
<td>6.5532</td>
<td>0.2546</td>
</tr>
<tr>
<td>5</td>
<td>1440.22</td>
<td>5.7150</td>
<td>0.1178</td>
<td>7.5692</td>
<td>0.3988</td>
</tr>
<tr>
<td>6</td>
<td>1728.26</td>
<td>5.7658</td>
<td>0.1266</td>
<td>7.8486</td>
<td>0.4350</td>
</tr>
<tr>
<td>7</td>
<td>2016.30</td>
<td>5.7658</td>
<td>0.1266</td>
<td>8.3058</td>
<td>0.4916</td>
</tr>
<tr>
<td>8</td>
<td>2304.35</td>
<td>5.9690</td>
<td>0.1613</td>
<td>8.2804</td>
<td>0.4886</td>
</tr>
<tr>
<td>9</td>
<td>2592.39</td>
<td>6.1214</td>
<td>0.1865</td>
<td>9.7790</td>
<td>0.6549</td>
</tr>
<tr>
<td>11</td>
<td>3168.48</td>
<td>6.5352</td>
<td>0.2546</td>
<td>10.8712</td>
<td>0.7608</td>
</tr>
<tr>
<td>13</td>
<td>3744.56</td>
<td>6.7564</td>
<td>0.2852</td>
<td>10.8204</td>
<td>0.7561</td>
</tr>
</tbody>
</table>

Table 4.21 : Axial True Strain Data for 6061-O Rings Compressed onto 2.54 cm Diameter Mandrels
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>Min. Min.</th>
<th>Max. Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Height $\epsilon_{\text{axial}}$</td>
<td>Height $\epsilon_{\text{axial}}$</td>
</tr>
<tr>
<td>2</td>
<td>576.09</td>
<td>5.3340</td>
<td>0.0488</td>
</tr>
<tr>
<td>3</td>
<td>864.13</td>
<td>5.4610</td>
<td>0.0723</td>
</tr>
<tr>
<td>4</td>
<td>1152.17</td>
<td>5.6388</td>
<td>0.1044</td>
</tr>
<tr>
<td>5</td>
<td>1440.22</td>
<td>5.7404</td>
<td>0.1222</td>
</tr>
<tr>
<td>6</td>
<td>1728.26</td>
<td>5.9690</td>
<td>0.1613</td>
</tr>
<tr>
<td>7</td>
<td>2016.30</td>
<td>6.2230</td>
<td>0.2029</td>
</tr>
</tbody>
</table>

Table 4.22: Axial True Strain Data for 6061 - 0 Rings Compressed onto 3.81 cm Diameter Mandrels

![Graph showing the effect of radial strain on axial true strain](image)

Figure 4.27: Effect of Radial Strain on Axial True Strain
4.12 Effect of Material

4.12.1 Wrinkling

The wrinkling characteristics of the 1.651 mm thick 6061 - O rings was compared with that of 1.6 mm thick copper rings. The height of the rings was 5.08 mm and the rings were compressed onto mandrels of diameter 3.175 cm. The copper rings could not be made to fail. Arcing between the ring and the mandrel was severe at high energies and it was decided not to continue the experiments at higher energies due to safety considerations. The table 4.23 is a listing of the wrinkling data for the copper rings. The wrinkling curves of the two materials are compared in the figure 4.28.

<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>No. of Wrinkles</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.65</td>
<td>574.87</td>
<td>13</td>
<td>(d_{\text{ring}} \approx d_{\text{mandrel}})</td>
</tr>
<tr>
<td>10.00</td>
<td>864.46</td>
<td>8</td>
<td>(d_{\text{ring}} \approx d_{\text{mandrel}})</td>
</tr>
<tr>
<td>12.00</td>
<td>1037.35</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>13.35</td>
<td>1154.06</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>15.00</td>
<td>1296.69</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>16.65</td>
<td>1439.33</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>20.00</td>
<td>1728.92</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.23 : Wrinkling Data For Copper Rings
4.12.2 Clamping Force

The clamping force data for the Cu rings is listed in table 4.24. The data is compared with that for 6061 - O rings in the figure 4.29.

4.12.3 Axial True Strain

The minimum and maximum axial true strain values for the copper rings are listed in the table 4.25. The data is compared with that for 6061 - O rings in the figure 4.30.
<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>Peak Load 1 (kg)</th>
<th>Peak Load 2 (kg)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.65</td>
<td>574.87</td>
<td></td>
<td></td>
<td>( d_{\text{ring}} = d_{\text{mandrel}} )</td>
</tr>
<tr>
<td>10.00</td>
<td>864.46</td>
<td></td>
<td></td>
<td>( d_{\text{ring}} = d_{\text{mandrel}} )</td>
</tr>
<tr>
<td>12.00</td>
<td>1037.35</td>
<td>13.013</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.35</td>
<td>1154.06</td>
<td>454.454</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.00</td>
<td>1296.69</td>
<td></td>
<td></td>
<td>data not available</td>
</tr>
<tr>
<td>16.65</td>
<td>1439.33</td>
<td>851.295</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20.00</td>
<td>1728.92</td>
<td>2505.036</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.24: Clamping Force Data for Cu Rings
Figure 4.29: Effect of Material on Wrinkling

<table>
<thead>
<tr>
<th>Energy (kJ)</th>
<th>E/m (kJ/kg)</th>
<th>Min. Height (mm)</th>
<th>Min. ( \varepsilon_{\text{axial}} )</th>
<th>Max. Height (mm)</th>
<th>Max. ( \varepsilon_{\text{axial}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.65</td>
<td>574.87</td>
<td>5.4864</td>
<td>0.0770</td>
<td>6.1976</td>
<td>0.1989</td>
</tr>
<tr>
<td>10.00</td>
<td>864.46</td>
<td>5.5626</td>
<td>0.0908</td>
<td>6.6294</td>
<td>0.2662</td>
</tr>
<tr>
<td>12.00</td>
<td>1037.35</td>
<td>5.6642</td>
<td>0.1089</td>
<td>6.9850</td>
<td>0.3185</td>
</tr>
<tr>
<td>13.35</td>
<td>1154.06</td>
<td>5.7658</td>
<td>0.1266</td>
<td>7.5946</td>
<td>0.4021</td>
</tr>
<tr>
<td>15.00</td>
<td>1296.69</td>
<td>5.8420</td>
<td>0.1398</td>
<td>7.3660</td>
<td>0.3716</td>
</tr>
<tr>
<td>16.65</td>
<td>1439.33</td>
<td>6.1722</td>
<td>0.1947</td>
<td>7.8740</td>
<td>0.4383</td>
</tr>
<tr>
<td>20.00</td>
<td>1728.92</td>
<td>6.3754</td>
<td>0.2271</td>
<td>8.5344</td>
<td>0.5188</td>
</tr>
</tbody>
</table>

Table 4.25: Axial True Strain Data for Copper Rings
Figure 4.30: Effect of Material on Axial True Strain
CHAPTER 5
DISCUSSION

5.1 Normalization of Energy

The normalization of energy with mass is based on the belief that the initial velocity imparted to the sample by the coil significantly affects the formability, wrinkling and springback characteristics observed. By holding the $E/m$ value constant between the different materials, an attempt has been made to hold the velocity constant. If $E$ is the energy discharged by the capacitor bank and $\eta$ is the efficiency of energy transfer to the metal sample, then

$$\frac{1}{2}mv^2 = \eta E$$

(5.1)

where, $m$ is the mass of the metal sample and $v$ is its initial velocity. The efficiency parameter, $\eta$ depends on several factors including the losses at electrical contacts, the geometry of the coil and the mutual inductance between the coil and the workpiece. The factors like contact losses and the geometry of the coil were kept constant throughout the entire study. However, the mutual inductance between the coil and workpiece depends on the geometry and conductivity of the workpiece. The conductivity of the different aluminum alloys and tempers differ from each other slightly. The conductivity of copper differs significantly from that of aluminum. The geometry of the workpiece changes when the height of the rings is varied. Thus, $\eta$ is not a constant for all materials. So the parameter $E/m$ is not too
accurate as a measure of velocity and is considered more as a first order approximation.

Further this approximation is more accurate for the sheet metal than for the rings due to two reasons.

1. The mutual inductance depends upon the geometry of the sample. In the sheet metal experiments, all the samples are of the same diameter. In the ring compression studies, sample height is different for some of the samples.

2. In the sheet metal experiments, there is a time lag between the launching of the sample and its plastic deformation. Thus, the metal blank has time to reach the peak velocity before it starts deforming. However, during ring compression, transfer of energy from the coil to the ring and the plastic deformation of the ring take place simultaneously. In this case, the peak velocity reached by the ring would be a function of the material flow stress.

5.2 Sheet Metal Forming

5.2.1 Asymmetry in the parts

The dies over which the metal blanks were formed are cone sections, which are axisymmetric shapes. However, the samples formed are non-axisymmetric. This is caused by the non-uniformity of the force field of the coil. The coil was hand-wound and the spacing between the turns of the coil was not consistent. Thus the samples to be thrown at an angle rather than vertically upward.
5.2.2 Wrinkling

Wrinkling is found to decrease monotonically with energy for all the materials. Wrinkling is eliminated at a particular value of \( E/m \) and at higher values of \( E/m \), there is no wrinkling. The figures 5.1 and 5.2 are photographs of the 1 mm thick 1100 - O and the copper samples (respectively) formed at different energies.

![Figure 5.1: Photograph of the 1mm thick 1100 - O samples formed at different energy levels](image)

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Two possible cases arise: (a) wrinkles are formed which are subsequently eliminated and (b) wrinkles do not form at all. Arguments have been presented in favour of both these cases as and when the relevant data is analysed and the arguments have been summarized at the end of this section.

The inertial ironing effect could contribute towards the ironing out of the wrinkles, if they are formed. The inertial ironing stress is a function of the sample velocity. As the energy used to form the sample increases, the sample velocity increases. This would increase the inertial ironing forces, thereby reducing wrinkling. The presence of the inertial ironing effect itself can be proved from the formability data. The major and minor strains observed in the samples formed at two different energy levels are listed in table 5.1. For
each energy, the grid circles were chosen along a line starting at the center of
the circle, passing through the corner and ending at the periphery of the
sample. The figure 5.3 is a plot of the major strains as a function of circle
number. It can be seen that the plastic strains seen on the wall portion of the
sample increase as the energy input into the sample increases. Further, on the
wall portion of the sample, the major strain in the circle increases as the
distance of the circle from the corner increases. These indicate the presence of
the inertial ironing forces.

Figure 5.3: Major strain for 1 mm thick sheet samples formed
at 2.725 kJ and 6.95 kJ
<table>
<thead>
<tr>
<th>Circle No.</th>
<th>( E = 2.725 \text{ kJ} )</th>
<th>( E = 6.95 \text{ kJ} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( e_{\text{radial}} ) or ( e_1 )</td>
<td>( e_{\text{circumferential}} / e_2 )</td>
</tr>
<tr>
<td>1 (center)</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>2</td>
<td>0.026</td>
<td>0.011</td>
</tr>
<tr>
<td>3</td>
<td>0.003</td>
<td>0.009</td>
</tr>
<tr>
<td>4</td>
<td>-0.022</td>
<td>-0.011</td>
</tr>
<tr>
<td>5</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>6</td>
<td>-0.013</td>
<td>-0.02</td>
</tr>
<tr>
<td>7 (corner)</td>
<td></td>
<td>0.052</td>
</tr>
<tr>
<td>8</td>
<td>0.179</td>
<td>-0.018</td>
</tr>
<tr>
<td>9</td>
<td>0.225</td>
<td>-0.029</td>
</tr>
<tr>
<td>10</td>
<td>0.240</td>
<td>-0.036</td>
</tr>
<tr>
<td>11</td>
<td>0.243</td>
<td>-0.057</td>
</tr>
<tr>
<td>12</td>
<td>0.249</td>
<td>-0.034</td>
</tr>
<tr>
<td>13</td>
<td>0.233</td>
<td>-0.044</td>
</tr>
<tr>
<td>14 (periphery)</td>
<td>0.271</td>
<td>-0.055</td>
</tr>
</tbody>
</table>

Table 5.1: Engineering Strains in the radial and circumferential directions for the 1 mm thick 1100-O samples formed at 2.725 kJ and 6.95 kJ

Another factor that would reduce the extent of wrinkling and possibly, even prevent the formation of wrinkles (i.e. in favour of case b) is the change in \( r \) value with strain rate. Recent ring expansion studies by Tamhane, Altyanova and Daehn [20] suggest a possible increase in \( r \) value of the material with energy. If similar material behavior were to be observed in sheet forming, then an increase in \( r \) value would cause an increased contraction of the material in the lateral direction. Thus, the material available for wrinkling...
would be reduced. If the contraction in the lateral direction is large enough, then no wrinkles would be formed.

From the figure 3.20, it can be seen that, for a particular value of E/m, the number of wrinkles is higher for a thin sheet compared to a thicker sheet. Wrinkling is a form of failure under buckling and it is a well established fact that thinner materials buckle more easily than thicker materials. Further, the inertial forces are due to the mass of the material and a thicker sheet would experience larger inertial forces. This also contributes to the reduced wrinkling in the thicker sheets.

The wrinkling curves of 1 mm thick 1100 - O, 1.6 mm thick 1100 - O and 1.28 mm thick 6061 - T6 are plotted in figure 3.25. The wrinkling curve for a 1.28 mm thick 1100 - O could be expected to lie between the curves for the 1 mm and 1.6 mm sheets. The T6 failed by tearing before the wrinkles were eliminated. However, in the range of energies at which it did not tear, there were more number of wrinkles for the T6 temper compared to the O temper at a particular value of E/m. This could be attributed to the higher strength of the T6 alloy. The proof stress of the 1100 - O alloys is in the range of 40 MPa to 50 MPa whereas the T6 alloy has a proof stress of 256.5 MPa. The ironing out of the wrinkles requires the flow of metal. For a particular applied force, more flow is possible for a softer metal compared to a harder one. Hence, the wrinkles can be eliminated more easily for a low strength material. The flow stress dependence of wrinkling can also be considered as an evidence of the formation of the wrinkles and their subsequent elimination as against wrinkles not being formed at all.
At a particular value of $E/m$, there are more wrinkles in the sample formed over the 30 degree die compared to the 45 degree die as shown in the figure 3.26. This is due to the difference in surface areas of the two dies. For a given length along the surface of the die, the surface area of the 30 degree die is lesser than that of the 45 degree die. Thus, the excess material in the lateral direction that causes wrinkling is more for the metal blank formed over the 30 degree die than the 45 degree die. A larger force and hence a larger energy is required to iron out this excess material in the sample formed over the 30 degree die. In other words, for a particular energy, more wrinkles remain on the sheet formed over the 30 degree die.

The samples formed by varying the distance between the metal blank and the die show that wrinkles were absent for “sample to die” distances of 0.375 cm, 1.588 cm and 2.858 cm, but that wrinkling was present for a distance 4.128 cm. This seems to indicate that wrinkling increases as the distance between the blank and the die increases. However, the author feels that this is an artifact of the poor vacuum level in the blast box. During the forming operation, the sample moves towards the die at a very high speed. If air is present between the sample and the die, it gets compressed as the time interval is too short for the air to move out. The compressed air has two effects: (a) An air pocket forms between the metal sample and the die which prevents the metal from taking the shape of the die, as was observed for the samples which were placed at distances of 1.588 cm, 2.858 cm and 4.128 cm from the die. As the “sample to die” distance increases, more air is trapped and the conformity between the die and sample shapes is lesser. (b) The air column causes
resistance to the motion of the sample and reduces its velocity. A larger air column reduces the velocity more. This is equivalent to forming the sample at a lower energy which accounts for the increase in the number of wrinkles. The author believes that, if the samples were formed in perfect vacuum, the stand-off distance would have no effect on wrinkling.

It can be seen from figure 3.27 that the wrinkling of 1 mm thick 1100 - O is very similar to that of the 0.8 mm thick copper samples. However, this similarity is a result of the contribution from several parameters - thickness, flow stress, r value and possibly other material parameters. A 1 mm thick copper sample would show less wrinkling than a 0.8 mm thick copper sheet. The proof stress of the copper is 144 MPa compared to a value of 42 MPa for the 1100 - O sheet. The higher strength of the copper sheet would contribute towards its increased wrinkling. Further, as was pointed out in section 5.1, the normalization of energy with mass is rather inaccurate for comparing aluminum with copper. A different normalization procedure would cause the curves to shift to the left or the right. Thus, unless the effect of the other parameters could be quantified and predicted and a more accurate normalization procedure used, it is not possible to isolate the effect of material, if any.

As was pointed out in the beginning of this section, the question of whether the wrinkles are formed or not has not been resolved. The arguments in favour of the wrinkles being formed and subsequently eliminated are as below.
1. If wrinkles are formed, they should have been ironed out by the inertial ironing forces. Wrinkling is found to decrease as the inertial forces increase (i.e. when either the velocity or the thickness of the sample increases).

2. In some of the samples formed, there is visual evidence of the wrinkles being formed and ironed out.

3. Harder materials wrinkle more.

The arguments in favour of the wrinkles not forming at all are as follows.

1. The increase in "r" value with strain rate would reduce / prevent wrinkling.

2. Let the sample be considered to be made up of several particles. As the sample velocity increases, it is more difficult for the particles to deviate from their trajectory and this would prevent wrinkling. Decrease in wrinkling with an increase in sample velocity supports this argument.

3. In samples formed at high energy, there is no variation in thickness in the sample along the periphery. If the wrinkles had been ironed out, the samples would exhibit a thickness variation. This means that the wrinkles did not form at all.

Thus, it is not very clear which of these cases represents reality. It is also possible that wrinkles never formed in some of the samples while in others, wrinkles were formed and then ironed out.
5.2.3 Springback

Most of the samples formed, irrespective of the material and temper had a bulge in the base of the sample. This also shows up as a peak in the springback curves close to the center of the sample. This bulge is not due to springback. The material in the portion of the bulge did not contact the die. This could be confirmed by the difference between the machine marks in the bulge portion and the rest of the sample. The bulge portion retained the rolling marks of the sheet material while the rest of the sample had picked up the machine marks on the die. One or both of two possible factors are believed to cause the bulge.

1. The force field of the coil varies significantly in the radial direction. The figure 5.4 is a photograph of a sample that was free formed (i.e. without placing any die in the path of the sample) at 3.38 kJ. The shape of the free-formed sample could be taken as a good representation of the force field of the coil. The center of the coil does not have any turns and hence the force field at the center is extremely weak or might even be completely non-existent. Hence, the force exerted on the center of the sample is very low and might not have been sufficient to make the metal contact the die.

2. As explained in section 5.2.2, the poor vacuum level in the chamber could have caused air to be trapped between the sample and the die which resulted in the bulge.

Most of the samples also exhibit a waviness towards the periphery, which increases with energy. The reason for this is not clearly understood and could possibly be due to some plastic wave effects.
Figure 5.4: Photograph of the sample free-formed at 3.38 kJ. The bottom surface of the sample was facing the coil before forming.

The figures 3.14, 3.15, 3.16, 3.17, 3.18 and 3.19 are the springback curves for all the samples of 1100 - O and copper that did not wrinkle. As was pointed out at the beginning of this section, the peak at the center is not due to springback. Thus, except for the waviness at the periphery at high energies, the springback in the samples consistently lies in the range of -0.2 mm to 0.3 mm, irrespective of material or temper. The negative values of springback represent the “springforward” effect, which has also been referred to by others in the literature, as was pointed out in Chapter I. However, the reasons for this springforward effect are not understood.

The low springback seen in EMF is well brought out by a different representation of the springback data. The figures 5.5, 5.6 and 5.7 compare the actual profile along the major axis of the samples with that of the die. The figure 5.5 is the profile of the 1.6 mm thick 1100 - O sample formed at 4.5 kJ.
Except for the small bulge at the center, the sample practically conforms to the shape of the die completely. The figure 5.6 is the profile of the 1.0 mm thick 1100 - O formed at 6.95 kJ and the springback in this sample is one of the highest. It is to be noted that the profile shown in the graph is magnified compared to the actual sample.

Three of the factors that can contribute to the low springback in electromagnetic forming have been identified. These are explained below. Apart from these, there could also be other factors affecting the observed springback.

1. Very high plastic strains are seen in the samples formed, some as high as 100% at some points. A high ratio of plastic strain to elastic strain will cause the springback to be low. The absence of lubricants in the EMF process contributes to the high plastic strains by increasing the friction between the die and the metal blank.

2. As was pointed out in Chapter I, Yamada et. al. [9] have proposed that compressive stress in the thickness direction reduce springback by causing the stress distribution to be more uniform. The ironing forces cause large "through thickness" compressive stresses in the samples formed and it is felt that these would contribute to a reduction in springback.

3. It is a well established fact that the metal samples are heated up during electromagnetic forming [5]. The temperature of the sample can be expected to rise upto 150 °C. For aluminum, this temperature is high enough to cause appreciable stress relaxation, which would reduce the springback. The effect of temperature rise is not expected to be significant for copper as its melting temperature is high.
Figure 5.5: Profile along major axis of 1.6 mm thick 1100 - O sample formed at 4.5 kJ compared with the die
Figure 5.6: Profile of 1 mm thick 1100 - O sample formed at 6.95 kJ compared with the die.
Figure 5.7: Profile of 1.6 mm thick 1100-O sample formed at 2.5 kJ compared with the die.
Even though the springback values presented are low, it is felt that the actual springback might be lower than the measured values due to two reasons.

1. The figure 5.7 is a plot of the profile along the major axis of the 1.6 mm thick 1100 - O formed at 2.5 kJ. The corresponding springback values for the sample are plotted in the figure 5.8. One of the assumptions in the analysis was that the springback at the corner of the sample is zero. This assumption was effected by picking three points on the corner of the die and aligning the XY plane of the CMM with the plane constructed through these points (refer section 3.5.1 for details). However, the corner itself has a radius and this seems to have introduced an error in the orientation of the XY plane. It can be seen from figure 5.7 that the sample profile is tilted (by a small clockwise rotation) with respect to the die profile. The right-hand corner of the sample does not coincide with that of the die, i.e. an assumption is violated. The effect of this tilt can be seen clearly in
A negative springback is seen in the wall portion on the left-hand side of the profile and a positive springback in the wall portion on the right-hand side. If this tilt is corrected for using more accurate data acquisition procedure, the springback values would be lower than the currently measured values. This tilt is seen in several samples.

2. The model of the CMM used, under ideal conditions has an accuracy of 0.0076 mm. However, when the springback data was measured, the CMM had not been calibrated for five years and its accuracy had dropped to about 0.05 mm. The springback values measured are very close to the resolution limit of the CMM and the accuracy of the data within this range is not very reliable. The actual springback values could be lower than the measured values. But, the data cannot be significantly higher as they have to lie within this range.

The springback trends could be summarized as below. At very low energies, the samples wrinkle and hence conformation to the die geometry is rather poor. At high energies, the springback is high towards the periphery of the sample. In a range of intermediate energies, there is excellent conformation of the sample shape to the die.

5.3 Ring Compression

5.3.1 Shape of Compressed Rings

Several of the compressed rings show a bulge, similar to a wrinkle. The bulge is due to the discontinuity in the force field caused by the slot in the single
turn coil. At the position of the slot, the force exerted on the ring is lesser than at other points and this ends up as a bulge in the compressed ring.

![Figure 5.9: Photograph of (a) rings compressed with the new single turn coil (b) rings compressed with the old single turn coil](image)

Prior to the ring compression studies described in this thesis, other ring compression experiments were done using a different single turn coil. The width of the slot in that coil was 0.254 cm. The figure 5.9 (b) is a photograph of rings that were compressed using the earlier coil. It can be seen that the bulge is pronounced in all these rings. While designing the coil for the current set of experiments (figure A.6), two modifications were made with the idea of eliminating the bulge.

1. The width of the slot was reduced to 0.064 cm.
2. The gap between the ring and the coil was increased slightly.
These modifications were expected to make the force field continuous enough to suppress the bulge. However, the success was only partial. The rings in the figure 5.9 (a) are some of the rings compressed in the current study using the second coil. For the 1.651 mm thick 6061 - O rings compressed onto a 3.81 cm diameter mandrel, the bulge was absent. For the 1.651 mm thick 6061 - O rings of heights 5.08 mm and 10.16 mm compressed onto a 3.175 cm diameter mandrel, the bulge was present at low energies. As the energy was increased, the size of the bulge reduced and the bulge disappeared at high energies. For all other rings, the bulge reduced in size as the energy was increased, but did not disappear even at high energies. The size of the bulge in these rings were smaller compared to rings compressed with the earlier coil.

Figure 5.10: Photograph of 1.651 mm thick 6061 - O rings compressed onto mandrels 3.175 cm in diameter
5.3.2 Wrinkling

Many of the trends observed in the rings compression experiments were similar to that in the sheet metal studies and these trends are also explained by the same reasons.

Figure 5.11: Rings of 1.651 mm thick 6061 - T6 compressed onto 3.175 cm diameter mandrels

All the materials exhibit a decrease in wrinkling as the energy is increased. The figure 5.10, 5.11 and 5.12 are photographs of the 1.651 mm thick 6061 - O, 1.651 mm thick 6061 - T6 and 1.6 mm thick copper rings (all of height 5.08 mm) compressed at different energies. The figure 4.13 shows this variation for the 1.651 mm thick 6061 - O rings. It can be seen that the first data point does not follow this trend. Referring to the corresponding data in table 3.4, it can be seen that the ring compressed at 2 kJ has a lower number of
wrinkles than the ring compressed at 3 kJ. This is due to the fact that the ring compressed at 2 kJ did not contact the mandrel. The decrease in the number of wrinkles with energy occurs only after the rings contact the mandrel. Prior to that, there is no correlation between the energy and the number of wrinkles.

As in the sheet metal samples, the decrease in wrinkling on contacting the mandrel is attributed to the ironing effect. Two factors support this reasoning. 1. As mentioned in the previous paragraph, wrinkling is reduced only after the ring contacts the die. Thus the die contributes towards the reduction in the number of wrinkles.

Figure 5.12: Rings of 1.6 mm thick copper compressed onto 3.175 cm diameter mandrels
2. The compressed rings exhibit several small, random bulges in the height direction along the circumference of the ring. This is believed to be caused by the excess material in the wrinkles which were ironed out.

The presence of the ironing forces itself is confirmed by the increase in axial strain with energy as shown in figure 4.15. Further, the height of the rings is more near the mandrel surface than at the outer surface of the ring. This is a further evidence for the presence of ironing forces. In the case of ring compression, changes in the $r$ value would not have any effect on wrinkling.

As seen from figure 4.16, wrinkling is reduced as the ring thickness increases. This could again be explained by noting that wrinkling is a form of buckling. It is a well established that thinner materials are more prone to buckling. Also, the inertial forces generated are larger and hence the ironing effect more for the thicker sheet.

For the normalization procedure used, i.e. on a E/m scale, wrinkling seems to decrease as the ring height is increased. This is a case where the normalization procedure used fails and the distinction between E/m and sample velocity needs to emphasized. As explained in section 5.1, the mutual inductance depends on the geometry of the sample. The mutual inductance is proportional to the area of the ring facing the coil and so, a larger current would be induced in a taller sample. This would cause a larger repulsive force on the ring and hence a higher velocity. Thus, for the same value of E/m used, the taller ring would acquire a higher velocity. The author believes that,
if the wrinkling data were to be plotted on a velocity scale, the two curves would approximately coincide.

The effect of material temper on wrinkling is shown in figure 4.22. The T6 temper wrinkles more than the O temper. As for the sheet metal, this is attributed to the higher strength of the T6 alloy. The 6061 - O has a proof stress of 75 MPa while the 6061 - T6 has a proof stress of 268.5 MPa. The T6 alloy requires larger ironing forces to remove the wrinkles.

Figure 5.13: Photograph of the original rings (5.08 cm O.D.) and compressed rings. The compressed rings have final I.Ds of (a) 2.54 cm (b) 3.175 cm (c) 3.81 cm

As can be seen from figure 4.25, rings can be subjected to large raidal reductions in a stable manner, i.e. without wrinkling using the electromagnetic forming process. The figure 5.13 is a photograph that shows both the original and the compressed rings subjected to different radial reductions. For the same value of E/m, the number of wrinkles is more for a larger radial compression as seen from figure 4.25. For the same launch
velocity, the velocity of the sample at the time of impact with the mandrel is lesser if the radial compression is more. The ironing force is dependent on the velocity of the ring during impact with the mandrel. Hence, the ironing force generated is smaller for the rings subjected to higher radial compression which manifests as a larger number of wrinkles.

The figure 4.28 is a comparison of the wrinkling of copper with that of 6061-O aluminum of the same thickness. For the same value of E/m, the copper rings show lesser wrinkling. Apart from any effects due to the material, the observed wrinkling is also affected by the strength of the two materials. The 6061-O has a proof stress of 66.3 MPa while the copper has a proof stress of 286.5 MPa. Thus, the effect of the material strength would be to cause more wrinkling in the copper rings than in the aluminum rings. However, since the copper exhibits lesser number of wrinkles at a particular E/m value, the effect of the material is to significantly reduce the wrinkling in copper.

5.3.3 Clamping Force

As was pointed out in section 4.4, the load Vs displacement graphs plotted while pushing the rings off the mandrel had either one or two peaks. This can be explained as follows. When the rings were compressed onto the mandrels, the forces generated by the impact were high enough to cause a small compression of the mandrels, especially at high energies. Immediately next to the compressed region, the mandrel would have expanded slightly. Also, in many cases, the rings did not remain where they impacted the mandrel, but usually moved up a small distance before coming to rest. The
rings were randomly pushed out in either of the two possible directions. Three cases arise.

1. If the ring had remained at the place of impact, it would have moved on one expanded portion of the mandrel independent of the direction it was pushed. Thus, this case would show one peak.

2. If the ring had moved up slightly and if it had been pushed away from the compressed region, then it would have had to move across only one expanded portion - the one on which it came to rest. Thus, for this case too, there would be only one peak.

3. Suppose the ring had moved up slightly and it had been pushed towards the compressed region. Then, firstly it would have had to move across the expanded portion on which it rested, which would cause the first peak. Then it would have moved into the compressed region causing a drop in the load. Then, it would have moved across the expanded portion on the other side causing a second peak.

This reasoning is supported by the fact that, whenever two peaks are observed, the spacing between them is approximately equal to the height of the ring.

The clamping force is found to increase with energy as shown in figure 4.14. The deformation of the ring and the mandrel can be considered to consist of two phases. In the first phase, the ring is compressed and it impacts the mandrel at a high velocity. The ring continues to compress along with the mandrel till the kinetic energy of the ring is expended. The compression of the mandrel could be purely elastic or both elastic and plastic depending on
the energy given to the ring. In the second phase, the mandrel recovers its elastic strain, i.e. it expands slightly. This causes the ring to expand too and when it finally comes to rest, it is in a state of tension. This causes a clamping force. As the energy increases, the inertial forces increase and the mandrel is compressed more. Within the elastic region, as the compression of the mandrel in the first phase increases, its expansion in the second phase increases and this causes a larger clamping force.

As seen from the figure 4.17, the clamping force increases as the ring thickness increases for the same value of E/m. For the same velocity of the ring, the force exerted by the ring on the mandrel increases as the mass of the ring increases. Hence, for the same velocity, the thicker sample exerts a larger force on the mandrel. This causes the mandrel to compress more. This, in turn, increases the subsequent expansion and hence causes a higher clamping stress. Further, for the same clamping stress, as the cross section increases, the clamping force increases.

Except for one data point, the clamping force for the taller ring is found to be more than that for the shorter ring, as seen from figure 4.20. As explained in section 5.3.2, the taller ring would have a higher velocity for the same value of E/m. A larger velocity would cause a larger inertial force. Further, for the same velocity, the mass of the taller ring would be more and hence the force exerted on the mandrel more. This would cause a higher clamping force.

For a particular value of E/m, the O temper is found to have a higher clamping force compared to the T6 temper. As explained in section 5.3.2,
because of the higher strength of the T6 alloy, the velocity of T6 ring at the instant of impact with the mandrel would be lower than that of the O temper ring. Hence the inertial forces experienced by the T6 ring is lower, resulting in a lower value of clamping force.

As can be seen from figure 3.26, for the normalization procedure used, the clamping force seems to be independent of the radial strain. As the radial compression increases, the inertial forces experienced by the ring at the time of impact with the mandrel would decrease. This could cause the clamping stress to decrease with increasing radial compression. However, a larger radial reduction causes an increase in the thickness of the ring. This causes an increase in the clamping force. Thus, there is a counter balancing of two effects.

The figure 4.29 compares the clamping forces for copper and 6061 - O aluminum. For a particular value of E/m, the copper rings show significantly higher clamping force. This is partly due to the fact that, for the same value of E/m, the copper rings might acquire a higher velocity because of their higher conductivity. Also, the coefficient of friction between the mandrel and the aluminum rings would be different from that between the mandrel and the copper rings. But these alone cannot account for the observed difference and other materials effects definitely contribute towards the higher clamping force in copper. However, it is not clear how exactly the material affects the clamping force.
It is to be noted that the load required to move the ring may be a result of other factors apart from frictional force. After the rings were pushed out, the inner surface of the rings were found to have a dull appearance compared to the outer surface. It is possible that some sort a bonding takes place between the ring and the mandrel locally at the point of contact, especially at high energies. Thus, the explanations given for the observed trends are, by no means, complete. The analysis of all the factors contributing to the observed trends is expected to be rather complex.

5.4 Usefulness of the Study

The results of this study would be of particular interest to the automotive industry. The industry has been striving to replace more and more steel components with aluminum parts in an attempt to reduce weight and increase fuel efficiency. The greatest challenge to this effort has been from the sheet metal parts because of the poor formability of aluminum by conventional means. For example, the strains required to form the corners of aluminum car doors (without wrinkling) are not easily achieved by conventional methods. However, these strains are well within the reach of the electromagnetic forming method. Attempts are being made by leading automotive companies to integrate the EMF process with the conventional stamping process. The sheet could be preformed to the extent possible using the stamping process and then the corners could be formed by the EMF process.

The low values of springback obtained using the EMF would be of interest to the aircraft industry where the dimensional accuracy of the components is
very critical. The can-making industry would find this method useful for surface embossing. A combination of a dull finish with a well polished surface inside it would make the cans more attractive to the customers.

The electromagnetic compression technique is already being used in the industry and the results of this study would hopefully lead to a better control of the process.
CHAPTER 6
CONCLUSIONS

6.1 Sheet Metal Forming

6.1.1 Wrinkling

1. The number of wrinkles decreases monotonically to zero as energy is increased.
2. For a particular value of $E/m$, the number of wrinkles decreases as the sheet thickness increases.
3. For a particular value of $E/m$, aluminum in the T6 condition wrinkles more than in the O temper. In general, higher material strength is expected to cause more wrinkling, all other factors held constant.
4. For a particular sample velocity, the sheet formed over the 30 degree die wrinkles more than the sheet formed over the 45 degree die.

6.1.2 Springback

1. At very low energies, the sheet metal wrinkles and does not conform to the shape of the die. At very high energies, a waviness is observed at the periphery of the sample which increases the springback. Over a range of intermediate energies, the springback is consistently low and lies in the range of -0.2mm to 0.3 mm.
2. The springback was found to be uniformly low, independent of the material or sheet thickness. The effect of material strength and die geometry could not be studied as the 6061 - T6 samples and the samples formed over the 30 degree semi apex angle die failed by tearing before wrinkling was eliminated.

3. A high ratio of plastic strain to elastic strain and large compressive stresses in the thickness direction (caused by inertial forces) are suggested as some of the reasons for low springback in EMF.

6.2 Ring Compression

6.2.1 Wrinkling

1. The number of wrinkles decreases monotonically to zero as energy is increased.

2. For a particular value of E/m, wrinkling decreases as ring thickness increases.

3. For a particular value of E/m, wrinkling decreases as ring height increases. However, it is possible that, for a particular sample velocity, wrinkling would be independent of ring height.

4. For a particular value of E/m, aluminum in the T6 condition wrinkles more than in the O temper. In general, higher material strength is expected to cause more wrinkling, all other factors held constant.

5. For a particular sample velocity, rings subjected to a larger radial compression wrinkle more. It was possible to compress rings to half their original diameter without wrinkling.
6. For a particular value are E/m, 6061 - O rings wrinkled more than copper rings. The effect of material was to decrease wrinkling in copper.

7. Inertial ironing forces are suggested as the reason for the reduction in wrinkling in the EMF.

6.2.2 Clamping Force

1. The clamping force monotonically increases as energy is increased.

2. For a particular value of E/m, clamping force increases as ring thickness increases.

3. For a particular value of E/m, clamping force increases as ring height increases.

4. For a particular value of E/m, clamping force for the 6061 alloy in the O condition is higher than in the T6 condition. In general, the clamping force is expected to increase as material strength decreases, all other factors held constant.

5. Clamping force is found to be independent of the extent of radial compression.

6. For a particular value of E/m, clamping force is significantly higher for copper than for 6061 - O alloy.

7. The reasons for the observed trends are rather complex and no conclusive statements could be made regarding the factors responsible for the trends.
APPENDIX A
DRAWINGS OF EQUIPMENT

A.1 Forty Five Degree Semi-apex Angle Die

Material: 4140 steel

Unless otherwise specified, all dimensions are in cm

Figure A.1: Drawing of 45 degree die used in Sheet Metal Studies
A.2 Thirty Degree Semi - apex Angle Die

Material : 4140 steel

Unless otherwise specified, all dimensions are in cm

Figure A.2 : Drawing of 30 Degree Die used in Sheet Metal Studies
A.3 Walls of Blast Box

Material: 1026 steel

Section AA

Unless specified, all dimensions are in cm

Figure A.3: Drawing of Walls of Blast Box Used in Sheet Metal Studies
A.4 Top Plate of Blast Box

Material: A36 steel

Section AA

1/2 in. pipe threads for 3/8 in. x 16 bolt

1/2 in. pipe threads

Bolt hole for 5/16 in. bolts. Typ. x 2

27.94

Hole for 3/8 in. bolt Typ. x 12

Ø = 0.9525

Unless otherwise specified, all dimensions are in cm

Figure A.4 : Drawing of Top Plate of Blast Box Used in Sheet Metal Forming Studies
A.5 Spacers Used In Sheet Metal Studies

Material: 4140

Unless otherwise specified, all dimensions are in cm

Figure A.5: Drawing for Spacers Used in Sheet Metal Studies

The spacers were of the geometry shown in figure A.5. The heights, \( s_1 \) of the different spacers are listed in table A.1.

<table>
<thead>
<tr>
<th>Spacer No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s_1 ) (cm)</td>
<td>2.540</td>
<td>1.270</td>
<td>0.635</td>
<td>0.318</td>
</tr>
</tbody>
</table>

Table A.1: Heights of Spacers Used in Sheet Metal Studies
A.6 Single Turn Coil

Material 6061 - T6

Bolts are 5/16 in. diameter.
All tolerances are +0.005, -0.000
Unless otherwise specified, all dimensions are in cm

Figure A.6: Drawing of Single Turn Coil Used in Ring Compression Studies
A.7 Alignment Fixtures

Material: Lexan

All dimensions in cm

Figure A.7: Drawing for Alignment Fixtures Used in Ring Compression

The height, s1 and the inner diameter, d1 of the fixtures used for aligning the different ring-mandrel combinations are listed in table A.2.

<table>
<thead>
<tr>
<th>$H_{\text{ring}}$ (mm)</th>
<th>5.080</th>
<th>5.080</th>
<th>5.080</th>
<th>10.160</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{\text{mandrel}}$ (cm)</td>
<td>2.540</td>
<td>3.175</td>
<td>3.810</td>
<td>1.250</td>
</tr>
<tr>
<td>s1 (cm)</td>
<td>1.270</td>
<td>1.270</td>
<td>1.270</td>
<td>1.016</td>
</tr>
<tr>
<td>d1(cm)</td>
<td>2.667</td>
<td>3.302</td>
<td>3.937</td>
<td>3.302</td>
</tr>
</tbody>
</table>

Table A.2: Height and Inner Diameter of the Alignment Fixtures Used in Ring Compression Studies
A.8 Spacer Used in Ring Compression Studies

Material: Lexan

![Diagram of Spacer Used in Ring Compression Studies]

All dimensions in cm

Figure A.8: Drawing for Spacer Used in Ring Compression Studies
APPENDIX B

LIST OF ELECTROMAGNETIC FORMING PATENTS

The following is a list of the electromagnetic forming patents issued since 1976.

1. Title : Magnetic Forming Process For Joining Electrical Connectors and Cables
   Inventors : Morris V, Duffner and Alexander Mintz
   Assignee : Grumman Aerospace Corporation, Bethpage, N.Y.
   Patent Number : 3,992,773
   Date of Patent : Nov. 23, 1976
   Abstract : An electrical connector having a deformable tubular shell between a cable and fitting manufactured by a process of magnetically deforming the shell at one end to the underlying cable and at the other end to the underlying fitting to provide a superior EMI and shielding integrity as well as good water tight seal without the need of potting the connection or providing special seal elements.

2. Title : Electromagnetic Dent Puller
   Inventors : Karl A. Hansen and Iver Glen Hendrickson
Abstract: An apparatus and method of electromagnetically pulling dents from conductive material. A coil is formed to direct an effective electromagnetic coupling to a limited area between the coil and a dented part. A non-conductive mold placed between the coil and the part has openings to overlie the dent. The coil is first energized with a slowly rising current then is energized with a fast pulsing countercurrent to generate a strong pulling electromagnetic coupling.

3. Title: Electrical Connector For Cables and Magnetic Forming Process For Same

Inventors: Morris V. Duffner and Alexander Mintz

Assignee: Grumman Aerospace Corporation, Bethpage, N.Y.

Abstract: An electrical connector having a deformable tubular shell between a cable and fitting manufactured by a process of magnetically deforming the shell at one end to the underlying cable and at the other end to the underlying fitting to provide a superior EMI and shielding integrity as well as a good water tight seal without the need of potting the connection or providing special seal elements.

4. Title: Forming Apparatus
Apparatus for forming hollow metal articles such as aluminum reflectors for Luminaires. The apparatus comprises a convex forming punch movable into a complementary hollow magnetic forming coil device. The forming punch is mounted on a base having an annular slot opening at the periphery of the forming punch and being connected to passages in the base for quickly evacuating the air between the workpiece and the punch prior to the magnetic forming operation.

5. Title: Inductor For Working Metals By Pressure Of Pulsating Magnetic Field

Disclosure is made of an inductor for working metals by the pressure of a pulsating magnetic field, wherein on the outer surface of a concentrator, which has a working opening to receive an article to be worked and a radial slot, there are provided annular grooves, the spacings between the annular grooves forming stiffening ribs of the concentrator; laid in said annular grooves are flat helical sections of a winding, the beginnings of each section enveloping an electrically
conducting rod arranged in a bore extending through the concentrator, being parallel with the axis of the working opening and being next to said annular grooves; the ends of each flat helical section are interconnected in parallel by means of a bus; in said concentrator ribs, there are provided threaded holes to receive screws whose but ends press upon the electrically conducting rod.

6. Title: Inductor For Magnetic Pulse Shaping of Metals

Inventors: Lev Timofeevich Khlmenko, Evgeny Nikolservich Degtyarev, Mikhail Ivanovich Baranov, Anatoly Vasilievich Legesa and Alexandr Tikhonovich Mezhuev

Patent Number: 4,067,216

Date of Patent: Jan. 10, 1978

Abstract: Disclosure is made of an inductor for magnetic pulse shaping of metals, wherein on the outer surface of a concentrator, having a radial slot and an opening to receive an article being worked, there are provided flutes with windings disposed therein; in the radial slot zone, the concentrator ribs are provided with rectangular-shaped grooves whose depth is equal to that of the flutes, said grooves extending perpendicularly to the plane of the radial slot and receiving electrically conducting segment-shaped inserts overlapping the radial slot and insulated from the concentrator by gaskets.

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7. Title: Inductor For Forming Metals By The Pressure Of A Pulsed Magnetic Field
Patent Number: 4,143,532
Date of Patent: Mar. 13, 1979
Abstract: An inductor for forming metals by the pressure of a pulsed magnetic field comprises a magnetic field concentrator with a coil inducing eddy currents therein, the concentrator being made up of electrically insulated dies with an opening for the workpiece, so arranged that the plane in which the concentrator is split extends along said opening. Such a design of the inductor permits improving the power characteristics thereof, simplifies its operation, extends its service life, and enhances its efficiency. It also permits forming a wide variety of components.

8. Title: Electromagnetic Force Machine With Universal Portable Power Supply
Inventors: Karl A. Hansen and Iver G. Hendrickson
Assignee: The Boeing Company, Seattle, Washington
Patent Number: 4,148,091
Date of Patent: Apr. 3, 1979
Abstract: An electromagnetic force (EMF) machine with a universal portable power supply is disclosed. The universal portable
power supply energizes either a multiple turn flux concentrator or a single turn flux concentrator. The flux concentrators produce magnetic fields that create an outward tension force adapted to perform non-destructive bond tests (tension proof loading) and/or dent removal operations on panels or the like. The power supply includes a slow current pulse subsystem; a fast current pulse subsystem; slow and fast crowbars; and, a firing control. The firing controls the production of pulses by the slow and a fast current pulse subsystem, and, the operation of the slow and the fast crowbars. The slow pulse subsystem, via the flux concentrator, slowly creates a magnetic field that penetrates the panel; the fast pulse subsystem, via the flux concentrator, rapidly decreases the magnetic field, whereby a negative field gradient is produced across the panel. The negative field gradient exerts the outward tension force on the panel. Further, a set of control switches control the magnitude of the current produced by the slow current pulse subsystem; and, determine the flux concentrator to which the slow and fast pulses are to be applied. Finally, a charging circuit controls the charge level of capacitor banks forming part of the slow and fast current pulse subsystems such that a predetermined ratio exists between the pulses produced by the slow and fast current pulse subsystems.

Inventors: Arthur W. McDermott and Ralph R. Welsh

Assignee: The Boeing Company, Seattle, Washington

Patent Number: 4,151,640

Date of Patent: May 1, 1979

Abstract: A method of making an EMR coil assembly having a split housing including a coil-retaining body member and ring member attached thereto, the EMR coil assembly including a coil having plurality of polyimide face sheets disposed between a polyester face sheet forming the outer wear surface of the coil and a major surface of the coil.

10. Title: Apparatus For Magnetic Forming Of Metals

Inventors: Lev T. Khimenko, Yakov M. Batkilin, Anatoly V. Legeza and Mikhail I. Puchkov

Assignee: Kharkovsky Politekhnichesky

Patent Number: 4,169,364

Date of Patent: Oct. 2, 1979

Abstract: An apparatus for metal forming under the pressure of pulsed magnet field comprises coils which are connected in series by means of flat buses, the extreme coils being provided with flat outputs arranged in parallel to one another along the coils; the flat buses are disposed intermediate the flat outputs and are insulated therefrom, with each of said flat buses being formed with a slot facing the coils and overlapped by the flat outputs.
Such apparatus construction permits its efficiency to be increased 25 to 40 percent.

11. Title: Electromagnetic Forming Apparatus

Inventor: Donald B. Weir

Assignee: L Maxwell Laboratories, Inc., San Diego, California

Patent Number: 4,531,393

Date of Patent: Jul. 30, 1985

Abstract: An electromagnetic forming apparatus having an expandable electromagnetic forming coil supported within an associated clamping press and having a pulse power system continuously operatively associated therewith to facilitate magnetic forming or swaging of conductive work pieces together. The forming coil employs a pair of conductive shaper halves conductively connected together in a single turn coil, the shaper halves having supported for relative movement therebetween while maintained in substantially parallel relation. The shaper halves have mutually cooperating forming recesses which receive the work pieces when the shaper halves are in open position and which define electromagnetic forming areas to swage the workpieces together when the shaper halves are closed and subjected to one or more power pulses. The apparatus finds particular application in electromagnetic forming of work pieces having enlarged or irregular cross-sections which prevent longitudinal insertion into or removal from fixed coils or shapers.
12. Title : Electromagnetic Forming Method By Use of A Driver

Inventors : Toshio Sano, Masaharu Takahashi, Yoichi Murakoshi and Kenichi Matsuno

Assignees : Agency of Industrial Science and Technology and Ministry of International Trade and Industry, both of Tokyo, Japan

Patent Number : 4,619,127

Date of Patent : Oct. 28, 1986

Abstract : An electromagnetic forming method is disclosed which effects desired forming on a given workpiece by disposing on the surface of the workpiece a driver obtained by superposing a highly electroconductive metal foil repeatedly over itself, opposing a primary coil to the driver, feeding electric current for forming to the primary coil thereby generating induced current in the driver, and allowing the workpiece to be formed by the resultant repulsive force exerted between the driver and the primary coil.

13. Title : Method And Apparatus For Reforming A Container

Inventors : Ronald W. Gunkel, Robert A. Cargnel, James R. Morran and Edward P. Patrick

Assignee : Aluminum Company of America, Pittsburgh, PA

Abstract : This invention provides a method for expanding at least a portion of a cylindrical sidewall of a generally cylindrically shaped, electrically responsive, metallic body. This method comprises the steps of retaining at least a first portion of the
metallic body, disposing a coil of electrically conductive material inside the metallic body, and energizing the coil to create an electromagnetic force sufficient to expand at least a portion of the generally cylindrical sidewalls of the metallic body outwardly of the original generally cylindrical shape. During such expansion, a fluid is introduced between the coil and the inside surfaces of the container to maintain positive gauge pressure as the sidewalls expand. This invention also provides an apparatus for expanding at least a portion of a cylindrical sidewall of a generally cylindrically shaped, electrically responsive, metallic body. The apparatus comprises a retaining mechanism for holding the metallic body, a coil of electrically conductive material, structure for disposing the coil inside the metallic body, and structure for energizing the coil sufficient to expand at least a portion of the sidewall of the metallic body. Means for maintaining positive gauge pressure during expansion is also included in the apparatus.

14. Title: Control And Monitoring Method And System For Electromagnetic Forming Process
Inventors: Dennis C. Kunerth and Gordon K. Lassahu
Assignee: The United States of America as represented by the United States Department of Energy, Washington, D.C.
Patent Number : 4,962,656
Date of Patent : Oct. 16, 1990
Abstract: A process, system, and improvement for a process for electromagnetic forming of a workpiece in which characteristics of the workpiece such as its geometry, electrical conductivity, quality, and magnetic permeability can be determined by monitoring the current and voltage in the workcoil. In an electromagnet forming process in which a power supply provides current to a workcoil and the electromagnetic field produced by the workcoil acts to form the workpiece, the dynamic interaction of the electromagnetic fields produced by the workcoil with the geometry, electrical conductivity, and magnetic permeability of the workpiece, provides information pertinent to the physical condition of the workpiece that is available for determination of quality and process control. This information can be obtained by deriving in real time the first several time derivatives of the current and voltage in the workcoil. In addition, the process can be extended by injecting test signals into the workcoil during the electromagnetic forming and monitoring the response to the test signals in the workcoil.

15. Title: Power Supply For Electromagnetic Proof Load Tester and Dent Remover

Inventor: Peter B. Zieve

Patent Number: 5,046,345

Date of Patent: Sep. 10, 1991
Abstract: A power supply for use with an electromagnetic force system used for dent removal or proof load testing, wherein the power supply includes slow and fast current pulse systems. The slow current pulse system includes a capacitor bank which is charged up to 1000 volts, while the fast current pulse system includes a capacitor bank which is charged up to 10 k volts. Control switches are provided for each system which result in discharge of the respective capacitor banks into a work coil adjacent the workpiece at selected times. A crowbar circuit is provided across the coil, and is triggered following discharge of the fast current pulse system. The crowbar circuit includes a series connection of several diodes to block the high negative reverse voltage and an SCR to block the low forward voltage, the SCR being triggered at the selected time to initiate conduction of the crowbar. An anti-parallel diode is connected across the SCR to prevent possible damage to the SCR caused by the rapid sequence of the reverse voltage and the rapidly rising current pulse.

16. Title: Sleeve Sizing Processes

Inventors: Abraham Cherian and William G. Herbert, Jr.

Assignee: Xerox Corporation, Stamford, Connecticut

Patent Number: 5,331,832

Date of Patent: Jul. 26, 1994

Abstract: A method and apparatus are disclosed for sizing preferably small diameter sleeves, wherein the method comprises the
steps in any effective order of: (a) providing an electrically conductive sleeve and a die; (b) positioning a portion of the sleeve in the die; (c) positioning a portion of an electrically conductive member inside the sleeve; (d) forming a direct electrical connection between the sleeve and the member; and (e) creating a magnetic field to expand the sleeve.

17. Title: Method of Sizing Metal Sleeves Using A Magnetic Field

Inventors: Abraham Cherian and William Herbert

Assignee: Xerox Corporation, Stamford, Connecticut

Patent Number: 5,353,617

Date of Patent: Oct. 11, 1994

Abstract: A method of sizing a sleeve of electrically conductive material includes the steps of inserting the sleeve in a die having a seamless inner surface, positioning a magnetic coil inside the sleeve in the die, and sealing the die after the insertion of the sleeve and the positioning of the magnetic coil. A vacuum is created inside the die to avoid air pockets between the outer surface of the sleeve and the inner surface of the die and the magnetic coil is energized to create a magnetic field to expand the sleeve against the inner surface of the die. The process may also be used to form a composite sleeve having an outer layer of material unresponsive to the magnetic field and an inner layer of electrically conductive material.

18. Title: Method For Compaction Of Powder-Like Materials
Inventors: Bhanumathi Chelluri and John P. Barber

Assignee: IAP Research, Inc.

Patent Number: 5,405,574

Date of Patent: Apr. 11, 1995

Abstract: Structure and a method for producing very dense bodies of material from powderous materials. A powderous material is placed within an electrically conductive container. A solenoid encompasses the electrically conductive container, and a large magnitude of electrical current is caused to flow through the solenoid or coil. As the electrical current flows through the solenoid or coil, large magnitudes of pressures are created upon the electrically conductive container, and the electrically conductive container is compressed, and the transverse dimension thereof is reduced. Thus, the powderous material within the electrically conductive container is very firmly compacted. A body of superconductive material of any desired size and shape can be produced by this method by the use of superconducting powderous material.

19. Title: Procedure and Apparatus For Cold Joining Of Metallic Pipes

Inventor: Alvin A. Snaper

Patent Number: 5,442,846

Date of Patent: Aug. 22, 1995

Abstract: Joinder of two adjacent segments of steel pipe having an outer diameter of at least 12 inches, by a bridging sleeve, the sleeve being joined to both pipe segments by magnetic forming.
Apparatus enabling the process includes a segmented ring-shaped coil brought together around the joinder, to form a complete coil circuit for magnetic forming.

20. Title: Method And Apparatus For Reforming A Tube
   Inventor: Gerald L. Wilson
   Assignee: Carrier Corporation, Syracuse, N.Y.
   Patent Number: 5,457,977
   Date of Patent: Oct. 17, 1995

Abstract: A method and apparatus for reforming, by either radially expanding or reducing an electrically conductive tubular workpiece. The method of the expansion embodiment comprises the steps of inserting an insulated electrical conductor into the tube; then making up an electrical circuit that includes the portion of the wall of the tube in series or parallel connection with the electrical conductor and a source of electrical power (C and SW), then applying a voltage across the circuit. The current flowing through the conductor and the tube produces a circumferential electromagnetic field between the conductor and the tube. The current in the tube, interacting with the magnetic field, produces a radially directed outward force on the tube. If the force is sufficiently great and of a duration longer than the time required for a sound wave to pass through the tube wall, the tube wall will radially expand and be permanently deformed. The method of the reduction embodiment comprises the additional step of inserting the
workpiece in an electrically conductive sleeve and the making up step comprises including the sleeve in the electrical circuit and arranging the workpiece and the conductor in parallel circuit relationship. The respective apparatus of the two embodiments implement the method of the invention. The expansion embodiment of the invention is particularly adapted to the expansion of tubes in plate fin and tube type heat exchangers.

21. Title: High Energy Impact Riveting Apparatus and Method

Inventors: David Michalewski, Joseph A. Dionne and Mark A. Siuta

Assignee: Gemcor Engineering Corp., Buffalo, N.Y.

Patent Number: 5,471,865

Date of Patent: Dec. 5, 1995

Abstract: A method and apparatus for forming a metal object such as upsetting a fastener in a workpiece wherein first and second coils are provided in close proximity to and in electromagnetic association with a forming tool adapted for forming the metal object and the first and second coils are supported in a manner allowing movement of the first coil relative to the second coil, and wherein an electric current pulse is supplied simultaneously to the first and second coils to produce a repulsive electromagnetic force sufficient to accelerate the first coil and driving the forming tool to form the metal object, the pulses being shaped in accordance with a characteristic of the metal object. The pulse shaping includes matching the
magnetic force based on the current pulse with the stress-strain characteristic of the metal object being formed. In high energy impact fastener installation apparatus, there is balancing of the applied force from both ends of the fastener during simultaneous impact and upset to eliminate transfer of force to the workpiece and supporting structure. Advantages include a relatively less drastic fall off of mutual magnetic field with separation of the two coils, decreased heat load, increased output force, low reactive force to the supporting structure, increased efficiency and the ability to tailor the magnetic force to synchronize with the force requirements of the metal object during forming, and a gap-free joint containing the metal object.
APPENDIX C

PUBLICATIONS OF THE HYPERPLASTICITY GROUP AT OSU


9. G. S. Daehn, M. Altynova, V. S. Balanethiram, G. Fenton, M. Padmanabhan, A. Tamhane, and E. Winnard, "High-Velocity Metal


REFERENCES


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