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Fundamental investigation of induction sealing of paper/foil
aseptic food packages

Yeh, Hong-Jun, Ph.D.
The Ohio State University, 1994
FUNDAMENTAL INVESTIGATION OF INDUCTION SEALING
OF PAPER/FOIL ASEPTIC FOOD PACKAGES

DISSERTATION

Presented in Partial Fulfillment of the Requirement for
the Degree of Philosophy in the Graduate
School of the Ohio State University

By

Hong-Jun Yeh, B.S., M.S.

* * * * *

The Ohio State University
1994

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Department of Welding Engineering
To my parents, my wife Su Ling
and my daughter Leslie
ACKNOWLEDGMENTS

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1.1 Development of Aseptic Food Packages

The food industry's constant pursuit for a better container that is inexpensive, attractive, portable, easy to transport and store, and better in food integrity protection has come to a conclusion -- aseptic processing and packaging. Nowadays, billions of units have been produced worldwide annually using aseptic packaging technique since 1980's according to Beverage World [1]. Figure 1.1 shows a typical aseptic processing and packaging system. Instead of using in-package sterilization, like in the traditional canning system, the aseptic processing and packaging system sterilizes the food product and packaging material separately; this makes it possible to use other packaging materials such as paperboard laminates or plastics other than the traditional metal can. The development of HTST (high temperature short time) and UHT (ultra high temperature) sterilization processes provides an efficient way to sterilize the food product in a very short time, meanwhile, keeping the product with the desired level of nutrition and quality. On the other hand, hydrogen peroxide mist with or without ultraviolet (UV) light are used to sterilize the aseptic packaging materials because of their lethal effect on microorganisms. After the
Figure 1.1 Aseptic processing and packaging flow chart
(revised from [2];[3])
sterilization process, the package is filled with the product and hermetically sealed under the sterile environment.

An aseptic food package can be defined as a hermetically sealed container holding the commercially sterile food which can maintain the integrity of its contents throughout a long shelf time [3]. The state of commercial sterility is defined as "the absence of microorganisms capable of reproducing in the food under normal nonrefrigerated conditions of storage and distribution and ..." [4]. The term "hermetically sealed" indicates that once the package is sealed, it has the appropriate mechanical properties to exclude the entrance of bacteria into the package or more explicitly to prevent the passage of microorganisms and gas or water vapor into or from the package [5]. As indicated above, three major concerns in the aseptic packaging always exist, first, sterilization of the packaging material, second, a sterile environment must be maintained during the filling of the food product, and finally, a hermetic seal is achieved to prevent the entry of the microorganisms into the package.

Prior to 1913, the first aseptic packaging of food was carried out in Denmark by Nielsen and a patent was granted for his aseptic conservation process in 1921 [6]. In the USA, a sterilization process was patented by Dunkley in 1917 with saturated steam of can and lid and subsequent filling of pasteurized product [7]. In 1933, a so called Heat-Cool-Fill sterilization system was developed by the American Can Company. Inside a closed pressurized chamber, the cans and ends were sterilized with saturated steam and then sealed. In the forties, Martin
developed an aseptic canning process in which empty metal cans were sterilized by superheated stream before filling with cold, sterile product. Later, in the 1950 Dole brought the first commercialized aseptic filling plant on the market [8]. In Switzerland, a dairy enterprise and machinery manufacturer (Alpura AG, Bern, and Sulzer AG, Winterthur) merged to develop UHT-sterilized and aseptically canned milk in 1953 [9]. It was not successful because of the high cost of the metal can. With the cooperation of Tetra Pak AB of Sweden which developed an aseptic cartoning system, the long shelf life aseptic milk package was successfully marketed in Switzerland in 1961 [10]. In 1969, the Aseptic Tetra Brik carton took the place of the tetrahedral shaped Tetra Pak because of the difficulties experienced during distribution and storage. During the last two decades, the development of aseptic food packaging was in full bloom. Especially, when hydrogen peroxide was first approved as a sterilant for aseptic packaging by the FDA in the US in 1981. Coming into the 1990's, there are six major categories of aseptic packaging systems that are commonly used: can systems, bottle systems, sachet and pouch systems, cup systems, bulk packaging systems, and carton laminates systems. Among these systems, the carton laminates systems are the most widespread packages for aseptic products such as dairy products, fruit juice, and other daily consumed beverages because of its low cost and superior characteristics for shipment and attractive displays.
1.2 Paper/foil Based Carton Laminates Aseptic Package

In this dissertation, the only type of aseptic package that will be dealt with is the paper/foil carton laminates package. Figure 1.2 shows two typical carton laminates aseptic food packages which can be found in the food market. For the carton laminates systems, after the lamination of the packaging material is completed, the package material is sterilized and partially sealed to form a pocket for the food. Then it is maintained sterile, filled with sterilized food, and finally hermetically sealed. The material for the inner food liner of aseptic packages is low density polyethylene (LDPE). Since polyethylene is a poor barrier for oxygen, an aluminum foil is laminated into the package to stop oxygen from reaching the food. Figure 1.3 shows a typical package material which is laminated as LDPE/aluminum foil/LDPE/paper board/LDPE. The inner LDPE layer can be heat sealed and provides a liquid barrier. The paperboard provides the package the required mechanical rigidity and acts as a medium for the printing and decoration. The outer LDPE protects the printing and enables the package to be folded and sealed.

1.3 Sealing of Paper/foil Carton Aseptic Food Packages

— Literature Review

Sealing is a very critical step in the manufacture of aseptic food packages because the production rate and shelf time, which are the most important elements in the food packaging industry, can be affected by the seal process time and seal quality. It must not only prevent the food from leaking out but also prohibit any air and particularly oxygen from
Figure 1.2 Typical carton/foil laminates aseptic food packages
Thickness in meters: (from left to right)

LDPE: 5.4E-5
Aluminum: 1.8E-5
LDPE: 6.0E-6
Cardboard: 2.7E-4
LDPE: 1.8E-5

Figure 1.3 Thicknesses and the cross-section of a carton/foil laminate
coming in contact with the food which may lead to food spoilage or contamination by organisms of public health significance. Although many researches have been done on the packaging process innovation, interaction between food and packaging material, package shelf time, microbiological aseptic, packaging materials improvement, and packaging cost analysis [11], very little research has been conducted specifically on sealing of the paper/foil carton aseptic food packages. Before we start with the aseptic food packages, let us first examine sealing of the polymer coated paperboard without foil. For traditional food industry, sealing of food packages such as polymer coated paperboard are usually done by hot air or hot tool sealing. Since hot tool sealing is very simple, not much attention was paid to it in the 70's. It was not until later in the 80's that the study of the sealing process began. The rapid growth of the packaging industry inspired the process optimization which led to the study of the sealing process. One area which gained much attention by researcher is using hot tack tensile test to evaluate the heat sealing process. This test method simulates the actual sealing process and test the seal strength by peeling the seal after a certain delay time. It can vary the sealing conditions such as sealing pressure, sealing time, delay time (holding time) to study the effects of these parameters on the seal strength. Thus, it is an important factor in determining the maximum packaging speed attainable for a particular heat sealing resin. Cramm [12] studied the causes of hot tack deficiencies in PE coated paperboard with a DTC Hot Tack Tester equipped with a laboratory extruder which can apply polyethylene
coating on 50# kraft paper. He found that corona treatment, coating thickness, extrusion temperature and extrusion rate have effects on hot tack strength. Halle [13] studied the hot tack strength of a variety ethylene polymers by using different comonomers, additives, and reaction conditions. He concluded that factors which determine a polymer's heat sealing characteristics can be classified into three groups: the polymer characterization variables (density, melt index, molecular weight distribution, additives, etc.), how the packaging film is made (film gauge, process conditions, treating, etc.) and the conditions of the heat sealing operation (sealing temperature, sealing pressure, dwell time, etc.). Roger and Tormala [14] used a similar hot tack tensile test to quantitatively evaluate the package performance at different sealing parameters to optimize the package sealing cycles. Only one publication was found regarding the sealing of paper/foil aseptic food package; Downes, et al [15] discussed the basic principles of the production of hermetic heat seal and the factors affecting the seal integrity. They identified that time, temperature, pressure are the most important variables in heat sealing of the aseptic food packages. Some of the sealing methods that were reviewed including impulse, ultrasonic, induction, and dielectric, sealing. They also reviewed some methods for examination and confirmation of the quality of the heat seals.

Although induction and ultrasonic sealing are currently used for the final hermetic seal in the aseptic food packaging industry, no in depth research publication has been found perhaps due to commercial competition.
1.4 Objectives

Although aseptic food packages have been used for decades, there is very little fundamental research that has been done on the sealing process. The information on techniques for sealing, seal defects, and how sealing parameters affect production rate and seal quality is still lacking. The objectives of the present study are the following:

1. Investigate possible sealing methods and choose promising ones for further study.
2. Establish the basic operation theory of sealing aseptic food packages.
3. Build sealing systems incorporated with data acquisition system which are capable of controlling the sealing parameters and measuring sealing data.
4. Evaluate and compare the sealing effectiveness for each sealing method based on speed and quality.
5. Study the effects of the sterilization on the sealability.
6. Perform an in depth study of the best sealing technique based on modeling and experiments.

In this research, the modeling and experimental study of the sealing process will provide the basis for future development of new sealing processes or improvement of conventional sealing processes for the food industry. The study of the sealing parameters optimization can elevate the manufacturing efficiency. The study of the effects of sterilization on sealing quality can help in developing new sterilization methods. All of these can eventually lead to a cost reduction for the manufacturing of the paper/foil carton aseptic packages without sacrificing food quality.
CHAPTER II
SEALING OF POLYETHYLENE FILMS

During the manufacture of a carton laminate aseptic package, the sealing process usually takes place between two thermoplastic layers. In order to control the seal quality of the package, it is important to study the basic processes of sealing polymer films. The process of fusion bonding, welding, or sealing of thermoplastic polymers like polyethylene film regardless of the techniques can be divided into four steps: heating of the surface, application of pressure, intermolecular diffusion, and cooling [16]. Before getting into the sealing process, there are some important characteristics of polymers which need to be considered.

1. Chemical composition and molecular structure:

Polymer is defined as a large molecule made of one or more repeating units (or mers) linked together by covalent bonds. For example, polyethylene consists of a long chain of covalently bonded carbon atoms with two hydrogen atoms sprouting out from each carbon atom (Figure 2.1). If the repeating units extend mainly in one dimension, the resulting molecular chain will be linear. If the repeating units extend in more than one dimension, the resulting molecular chain could be either branched or cross-linked. In cross-linked polymers, the
Figure 2.1 Molecular structure of polyethylene[15]
molecular chains are linked together which makes it impossible to reshape this type of polymers with heating - so called thermosets. Unlike cross-linked polymers, the linear and branched polymers can be softened, reshaped and melted with increasing temperature - so called thermoplastic. As the definition suggests, only the thermoplastic polymers can be welded. Under the different fabrication conditions such as temperature, pressure or stress, and cooling rate, the molecular chains structure may be different for the same thermoplastic polymer such as polyethylene which also experience different physical properties (Figure 2.2).

2. Molecular weight and molecular weight distribution:

In a practical industrial polymerization process, the length of the molecular chain produced varies considerably i.e. the degree of polymerization of different molecules is different. Therefore, polymers usually have a distributed molecular weight rather than a uniform molecular weight (Figure 2.3). A typical average molecule weight for low density polyethylene is around 20000 g/mol. Some mechanical properties are dependent on the average molecular weight and molecular weight distribution. For example, the tensile strength, elongation at break, and impact strength, increase with increasing average molecule weight. Narrower molecular weight distribution polymers usually have higher mechanical strength and higher, narrower range of process temperatures (Figure 2.4).
Figure 2.2 Different structure of HDPE LDPE and LLDPE resins[2]
Figure 2.3 Distribution of molecular weights in a typical polymer[17]
Figure 2.4 Relationship between molecular weight distribution and sealant properties[2]
3. Morphology and physical properties:

The thermoplastic polymers are either amorphous or semicrystalline which mean the molecular chain structure can be either linear or branched (Figure 2.5) and can be reshaped and melted when heating. For amorphous polymers, the molecules are motionless at low temperature. As the temperature increases, the atomic vibrations begin. When the glass transition temperature is reached, the atomic vibrations of neighboring atoms become cooperative and result in the motions of segments of molecular chains. At this time, the amorphous polymers become ductile. So do the amorphous regions in the semicryatalline polymers. Figure 2.6 shows the modulus versus temperature curve of a typical amorphous polymer. By contrast, for semicrystalline polymer which have both amorphous and crystalline regions, there exists two thermal transitions when heating: the glass transition for the amorphous region and the crystalline melt transition for the crystalline region. For the crystalline region in a semicrystalline polymer, once the temperature is higher than the crystalline melt temperature, the melting process begins where an ordered crystalline structure becomes random and the rearrangement of the molecular chains occurs. Figure 2.7 shows that there are two transitions in the modulus versus temperature curve of the semicrystalline polymer. Therefore in order to process amorphous or semicrystalline polymers, the process temperature must exceed glass transition temperature or melting temperature respectively.
Figure 2.5 Morphology of thermoplastic polymers [15]
Figure 2.6 Modulus versus temperature for an amorphous polymer[18]
RELATIVE MAGNITUDES OF DROPS IN $E$ AT $T_m$ AND $T_g$ ARE A FUNCTION OF THE DEGREE OF CRYSTALLINITY

Figure 2.7 Modulus versus temperature for a semicrystalline polymer[18]
Crystallinity is a big factor in determining the bulk material properties of polymers. For example, HDPE has a degree of crystallinity at 60 - 95% which is higher than LDPE at 40 - 60% [2]. Table 2.1 shows the difference in some typical properties of LDPE and HDPE. Although the HDPE has higher strength because of its higher crystallinity, the LDPE is more extensively used in the food packaging industry thanks to advantages like lower melting temperature, flexibility, toughness and clarity. Other properties like specific heat and thermal conductivity are very important in analyzing the heat flow during the sealing process.

2.1 Heating of Surface

Different sealing techniques actually differ primarily in the heating method that is used. The sealing process can be classified as [19]:

1. External heating methods: external heating energy is directly applied onto the surface of the part to be fusion joined.
   --Convection: hot gas sealing

2. Internal heating methods: heating energy is produced by mechanical motion which induces molecular vibration and friction at the joint interface.
   --ultrasonic sealing, vibration sealing, spin sealing

3. Electromagnetic heating: heating energy is transferred by electromagnetic waves onto the joint interface
   --laser/IR sealing, microwave sealing, dielectric sealing, resistance sealing, and induction sealing
Table 2.1

Typical Properties of Low Density and High Density Polyethylene[18]

<table>
<thead>
<tr>
<th>Property</th>
<th>LDPE</th>
<th>HDPE</th>
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<tr>
<td>density (kg/m³)</td>
<td>910 - 925</td>
<td>941 - 965</td>
</tr>
<tr>
<td>specific heat (J/kg·K)</td>
<td>2315</td>
<td>1855</td>
</tr>
<tr>
<td>thermal conductivity (W/m·K)</td>
<td>0.48</td>
<td>0.33</td>
</tr>
<tr>
<td>tensile strength (MPa)</td>
<td>4.1 - 15.9</td>
<td>21.4 - 37.9</td>
</tr>
<tr>
<td>tensile modulus (MPa)</td>
<td>96.5 - 262</td>
<td>414 - 1250</td>
</tr>
<tr>
<td>melting temperature (°C)</td>
<td>95 - 130</td>
<td>120 - 140</td>
</tr>
</tbody>
</table>
Different materials require different levels of heating. For semicrystalline polymer like polyethylene, in order to let flow and diffusion occur, the melting temperature of polyethylene must be exceeded. As discussed in the previous section, when the density of the polyethylene increases, the degree of crystallinity increases. As a result, the temperature required to melt HDPE is higher than LDPE. This is one of the main reason why LDPE has been the most commonly used material for sealing applications. Therefore, for the sealing of aseptic food packages, the time required for heating will be the time needed to heat up the LDPE layer above the melting temperature of LDPE around 95 - 130°C.

2.2 Application of Pressure

When a molten LDPE layer is created at the interface, two parts must be pressed together in order to form intimate contact. The purpose of the applied pressure is to deform and flow the molten polymers at the interface to overcome the surface roughness and squeeze out air. Generally, the hold pressure for the sealing processes is low except for internal mechanical heating, such as in ultrasonic sealing, which requires much higher pressure for the viscoelastic heating to take place. In the case of ultrasonic sealing aseptic food package, in addition to the high static pressure the dynamic compressive stresses from the ultrasonic horn may lead to the cracking of the aluminum foil underneath the LDPE film. Once the LDPE is melted, the flow behavior during the pressing process is dominated by squeeze flow mechanisms. In ultrasonic sealing, the aluminum foil at the joint interface will be
broken and squeezed outward of the joint area along with the molten LDPE layer. With external heating methods, such as induction and IR heating, the breakage of the aluminum foil is unlikely to occur because a low holding pressure is sufficient to achieve the sealing.

2.2.1 Squeeze Flow Analysis

In order to determine the effects of the holding pressure on the breakage of the aluminum foil, it is necessary to do a squeeze flow analysis to figure out the resulting tensile stress acting on the aluminum foil due to the holding pressure. A complete squeeze flow model is a complicated process. It requires to consider problems from thermal, fluid, rheology, inertia, and surface tension etc. The main purpose of the squeeze flow analysis in this case is to determine the breakage of the aluminum foil which caused by the shear force of the squeezed molten polyethylene applied on it. Therefore a simplified model was first studied to predict the tensile stress on the aluminum foil due to the squeeze flow. Squeeze flow model dominates the forging step of the sealing process. During the heating stage, when the melting temperature of LDPE is reached the molten layer begins to be squeezed outward of the joint area due to the externally applied pressure. The amount of squeeze out depends on the level of the applied pressure. If the pressure level is too high, the aluminum foil will be broken and squeezed out along with the molten layer. Therefore, the squeeze flow analysis is essential to determine the relationship between the level of pressure and the breakage of the aluminum foil.
The 2-D squeeze flow model for the sealing process can be simplified as a molten polymer layer been squeezed between two parallel plates (Figure 2.8). By assuming Newtonian liquid behavior for polyethylene melt, the relationship between the applied force and decreasing molten layer thickness can be described as following[19]:

\[
\frac{dh}{dt} = \frac{-Fh^6}{4\mu WL^3h_0^3}
\]  

(2.1)

or

\[
\frac{1}{h^5} - \frac{1}{h_0^5} = \frac{5Ft}{4\mu WL^3h_0^3}
\]  

(2.2)

where

- \( F \): applied force
- \( \mu \): viscosity
- \( h \): thickness of the molten layer
- \( L \): width of the molten layer
- \( W \): length of the molten layer

the average velocity in x direction can be defined as

\[
\bar{U} = \left[ \frac{dL}{dt} \right]_{h=h_s}
\]  

(2.3)

from conservation of mass

\[
L_0h_0 = Lh = \text{constant}
\]  

(2.4)

\[
\bar{U} = \frac{L_0}{H_0} \frac{dh}{dt} \bigg|_{h=h_s} = \frac{Fh_0^2}{4\mu WL^2}
\]  

(2.5)

For a Newtonian fluid the shear stress can be calculated as
Figure 2.8 Schematics of the simplified 2-D squeeze flow model
Finally the shear stress can be related to the applied force as

\[ \tau = \mu \frac{dU}{dy} = \mu \frac{\bar{U}}{h_0} \]  

(2.6)

By considering the shear force, as a tensile force acting on the thin aluminum foil, if the resulting tensile stress is greater than the tensile strength of the aluminum foil then the foil will break.

2.3 Intermolecular Diffusion

Intermolecular diffusion across the bonding interface is an essential process to create the bond strength. The diffusion process takes place when two separate molten polymer layers are pressed together and let the chain molecules move across the interface to create chain entanglement. Many studies have been done on the healing of the polymer - polymer interface. Usually the motion of chain molecules in molten polymers is studied as a problem in molecular statistical physics. De Genns [20] developed the reptation theory which considered the motion of a single chain molecule wriggling along a tortuous path formed by the adjacent chains. The time for complete healing, \( \tau_0 \), is related to average interpenetration distance \( x_0 \) and reptation diffusion coefficient \( D_c \) as follows [21]:

\[ x_0 \propto (D_c \tau_0)^{1/3} \]  

(2.8)

The effect of temperature on \( D_c \) can be described as [22],
\[ D_c = D_{c0} \exp \left[ \frac{E_a}{RT} \right] \]  

where \( E_a \) is the activation energy, \( T \) is the absolute temperature, and \( R \) is the universal gas constant.

Although the above relations have been verified by experiments only for the amorphous thermoplastics at temperatures above the glass transition temperature \( T_g \), the theory can also be applied to semicrystalline polymers like LDPE as long as the crystals are fully melted and the chain molecules are random i.e. the temperature of the semicrystalline polymer is higher than melting temperature \( T_m \). It is very difficulty to measure the rapid diffusion time for semicrystalline polymers because \( T_m \) is usually much higher than \( T_g \). In order to estimate the diffusion time for semicrystalline polymers, it is necessary to use the results from the experiments with amorphous polymers.

For semicrystalline polymer like LDPE, the time for complete healing \( \tau_0 \) at temperature above \( T_m \) can be estimated by extrapolating the data measured for similar amorphous polymers around \( T_g \). Jud et al [22] conducted experiments to evaluate the activation energy for the reptation diffusion coefficient for PMMA. By combining the two equations mentioned above, one can estimate healing time for LDPE at \( T_2 = T_g + 225^\circ K \) as follows:

\[
\frac{\tau_0(T_1)}{\tau_0(T_2)} = \frac{D_c(T_2)}{D_c(T_1)} = \exp \left[ -\frac{E_a}{R} \left( \frac{1}{T_2} - \frac{1}{T_1} \right) \right]
\]

From Jud et al, we have \( E_a = 274E3 \) J/mole, \( \tau_0(390^\circ K) = 10 \) min, and \( T_g = 375^\circ K \) Then, \( \tau_0(T_0 = 375+225^\circ K) \) for LDPE can be estimate to be at 8.6E-11 seconds. Based on this estimate, the complete healing for
semicrystalline like LDPE at T > T_m is considered as instantaneous compared to the time required for flow and wetting. Although LDPE is quite different from PMMA, the molecule weight is of the same order of magnitude and even with some error in the estimate, τ₀ for LDPE will still be too short to be considered for time delay compared to other process times such as heating, flow, and wetting time.

2.4 Cooling

Cooling is the process when the melted thermoplastic polymer resolidifies to give structural strength. For semicrystalline material, like LDPE, it must recrystallize to obtain their final microstructure. Too fast or too slow cooling may have some effects on the growth of crystallinity and spherulite which may result in a change of the mechanical properties of the bonded layers. For aseptic food packaging, since the failure of the material always occurs at the paper, the main concern is the minimum cooling time required to obtain the joint strength not the particular mechanical properties.

A complete cycle for sealing a package starts from heating the package material, pressurizing and joining, and ends with holding the joint until enough cooling of the package is obtained to produce the required seal strength. Usually the time needed for a complete cycle with a good seal strength is defined as the cycle time. Accordingly, there are three sealing parameters namely heat time, hold pressure, and hold time which are implemented to make sure the bonding is achieved in the shortest time. Heating and pressurizing processes can be done at the same time or sequentially, such as ultrasonic sealing or hot tool sealing.
If they are sequential then there is a change over time between the heating and pressuring processes. Therefore the cycle time can be the total of heat time and hold time or in some cases including change over time. First, the surfaces of the two PE films are heated until melting occurs. Controlling heating time is to insure that only sufficient melting of the polymer at the joint interface is obtained without overheating. Then a preset pressure is applied to have intimate contact of the molten layers for a period of holding time until the intermolecular diffusion which leads to the polymer chain entanglement and cooling are complete. These three parameters sometimes are interrelated, for example, in ultrasonic sealing, higher holding pressure may reduce the heat time that is required to melt the polyethylene surfaces. Another important factor that affects the seal quality is the uniformity of the melting along the interface. If the temperature distribution across the sealing area is not uniform, a hermetic seal cannot be produced.
CHAPTER III

METHODS FOR SEALING ASEPTIC FOOD PACKAGES

3.1 Overview of Sealing Methods

Like fusion bonding the polymer film, a variety of methods are available for sealing aseptic paperboard/foil packages as long as they can melt the film efficiently. Different methods primarily differ in the heating mechanism that is utilized. Induction and ultrasonic sealing are commonly used in the food industry for final hermetic seal of the packages because of their high process speed. In applications other than final hermetic seal, hot air or hot tool sealing is used to form a partially open carton before proceeding to the filling process. Table 3.1 gives a list of possible methods for sealing polymer films. Based on the structure of the paper/foil aseptic food package material some of the techniques are not applicable for sealing. The resistance sealing usually is a good candidate for sealing as long as there is a good conducting medium such as aluminum at the joint interface. But in order to create a current path, the electrodes must directly contact the aluminum. For this particular sealing case, the aluminum foil is always under the polyethylene coating which make it very difficult to have direct contact with the electrodes. Meanwhile there is no way to control the current path in the aluminum layer which means the heating area is not controllable. Therefore
Table 3.1

List of possible methods for sealing polymer films

1. Hot tool sealing
2. Hot gas sealing
3. Impulse heat sealing
4. Resistance sealing
5. Friction sealing
6. Vibration sealing
7. Microwave/dielectric sealing
8. IR sealing
9. Laser sealing
10. Ultrasonic sealing
11. Induction sealing
resistance sealing was not considered for further study. Microwave and dielectric sealing were not considered for further study because they cannot heat up the polyethylene, and the aluminum foil, which cannot be used in both techniques, is always laminated inside the package material. Friction and vibration sealing can also be eliminated from further study due to the difficulties in holding the films during the sealing process. Impulse sealing is more or less like hot tool sealing. Instead of using the hot tool, a nichrome ribbon is positioned between a bar insulator and a Teflon cover. When the parts are pressed between two bars, an electric current is passed through the nichrome ribbon. After the parts are melted, the current is turned off and the seal is cooled. This method is usually used in sealing food package which are made of polymer film. But for the paper/foil aseptic food package, the heat cannot be efficiently transferred through the thick paperboard to melt the polyethylene layer. As a result, a change over time like in the hot tool sealing is also required. Therefore this method is eliminated. A preliminary study on the process speed and seal quality for the remaining methods was conducted to determine which methods are worthwhile for further study.

3.2 Hot Tool Sealing

Traditional hot tool welding uses a heated metal plate or any other geometry which is brought into contact with the joint surfaces. The heat is transferred from the heated tool into the surfaces by conduction. Immediately after the joint surfaces are melted, the parts are removed
away from the heated tool, pressed together with a preset pressure and cooled. Figure 3.1 schematically show the typical steps during the hot tool sealing. For sealing of the thin food package which is made of just polymer film, since the hot tool can melt through the film, the heating and forging process can be done at the same time. Because of its simplicity, it is frequently used in food industry for sealing plastic pouches, bags etc. For the case of sealing aseptic food package, the hot tool cannot melt through the laminate because paperboard prevents the efficient heat transfer between the hot tool and polyethylene film. Therefore it is necessary to use the traditional hot tool welding technique where the heating and forging are separate.

Similar to other sealing process there are some important sealing parameters as follows:

1. Hot tool temperature
2. Heating time
3. Heating pressure
4. Holding pressure or sealing displacement
5. Change over time
6. Holding time

Different materials usually have a different set of optimal sealing parameters. For sealing of aseptic food packages, the hot plate temperature should be at least higher than the melting temperature of the polyethylene. But the hot plate temperature can reach up to 350 °C to get a shorter heating time without destroying the chemical
Step 1 - Heating under pressure

Step 2 - Heating with no pressure

Step 3 - Change over

Step 4 - Cooling

1, 7 - Parts to be welded  
2, 6 - Molten layer  
3, 5 - Teflon layer  
4 - Hot plate

Figure 3.1 Stages of hot tool sealing[23]
composition. A typical pressure profile during the sealing process is shown in Figure 3.2. During the heating stage, the pressure is kept low as long as it is enough to have the efficient heat conduction. During the forging stage, the pressure is relatively high and it is a very important parameter in controlling the squeeze out of the molten layer. Another way to control the squeeze out is to control the sealing displacement instead of pressure. Being unable to do the forging and heating at the same time, there is always a change over time between the completion of the heating and the beginning of the pressing stage. This elapsed time is a major disadvantage of the process because it cools off the molten joint surfaces before they can be joint together. Moreover, the Teflon coating or any other mold release agent on the hot plate can cause some contamination at the joint interface and result in low seal strength.

With a 280 °C hot plate temperature, 0.5 second heating time, the package material can be melted and sealed with a peel strength limited by the cardboard strength. But there still exists a change over time of at least 0.4 seconds which leads to a longer process time. Based on these observations, it is suggested that hot tool sealing could be used for sealing aseptic food packages. But the longer process time and possibility of contamination present a drawback in choosing this method.

3.3 Hot Gas Heating

The principle of hot gas sealing is to force a heated gas to flow over the joint areas or filler material. After the areas are melted, they can be jointed together. The thermal energy is transferred into the parts by
Figure 3.2 Sealing pressure variation during hot tool sealing[23]
convection. The technique is usually used in fabrication of large plastic structures which require manual flexibility.

In the traditional hot gas welding, there is a filler material between the joint areas. Once the joint areas and the filler material are melted and flowing, the joint can be created without external pressure. But for the application of sealing aseptic food package, there is no filler material and the sealing pressure is required to create intimate contact after the joint areas are melted. The sealing steps are similar to the hot tool sealing except that the heat source is replaced by noncontacting hot gas. The sealing parameters include the following:

1. Hot gas temperature
2. Hot gas pressure
3. Heating time or travel speed
4. Holding time
5. Change over time
6. Holding pressure

The hot gas temperature should exceed the melting temperature of the polyethylene film, and be kept below 350 °C to prevent chemical decomposition of the material. Setting the gas pressure is used to control the amount of hot gas flow rate according to the size of the nozzle. Heating time or travel speed are used to control the amount of heating depending on whether it is a stepwise sealing process or a continuous sealing process. For a stepwise sealing process, longer process time is expected due to the change over time. A preset sealing pressure is
applied to bring the melted joint areas together to let the diffusion and cooling occur and create a joint.

Hot gas can melt and seal the package material with a hot gas temperature of 250 °C, 10 psi gas pressure and about 0.5 second heating time. The seal quality is comparable to that of other methods. The major advantage over the hot plate sealing is that there is no direct contact of the heating element with the polyethylene film. But on the other hand, there are some disadvantage such as energy loss through the gas flowing outside the joint areas during the heating. Hot gas sealing is a good choice for sealing aseptic food package especially for continuous sealing process from economical point of view because of the low equipment and gas heat cost. But from the engineering point of view, the inefficient heating and the difficulty to control uniformity of heating during sealing puts hot gas sealing in a disadvantageous position.

3.4 Laser Sealing

Laser heating has the same characteristic as IR that is the radiation energy carried by electromagnetic waves. But unlike the IR lamp the wavelength of the laser light is fixed and can be focused to a spot as small as a few thousands of inches in diameter. The resulting powerful high energy density radiation beam can melt the polymers almost instantly. One of the important technical aspects regarding the laser heating of the polymers is the wavelength of the particular laser. CO₂ gas laser has a wavelength of 10.6 µm. By contrast YAG laser has a much shorter wavelength of 1.06 µm. Like the IR heating, in order to
have an efficient heating, the peak absorption wavelength of the polymer should stay as close as possible to the laser wavelength. For this reason, YAG laser is more suitable for polyethylene because the peak absorption wavelength of LDPE is around 1.7 μm (Figure 3.3). But the polyethylene film on the packaging material is so thin that the laser beam can penetrate the polyethylene layer. This explains why both CO₂ and YAG laser can melt polyethylene film efficiently. By using a simple fixture, the laser beam is applied to the interface of the two samples while a small holding pressure is applied (Figure 3.4). CO₂ and YAG laser heating can melt the polyethylene film very quickly or even burn through the packaging material depending on the power input. The joint can be created in less than a half second with a beam diameter of 1/8 inch and less than 50 watts of power output with a peel strength limited by the failure in the cardboard.

A typical laser heating assembly can cost from $10,000 to $500,000 depending on the power output and other options. The maintenance and material supplies cost are relatively high. Due to this economic drawback, potential applications are limited to either high production or expensive production pieces. But for the sealing of food packages, it is questionable that the high cost can be offset by increased process speed.

3.5 Infrared Sealing

Infrared heating is the radiation energy being carried by electromagnetic waves and eventually reflected, transmitted and absorbed by the material surface depending on the IR wavelength (0.1-
Figure 3.3 Spectra of the laminate and components showing the wavelengths selected for identification of each component. (where absorption is the first derivative of log 1/R) [24]
V: Travelling speed of the laser beam

P: Applied pressure

Figure 3.4 Schematics of laser sealing of aseptic food packages
100 microns) and the surface condition of material. But only the absorbed radiation energy can be converted into heat and melt the surface. The relationship between these three indices is as following:

\[ \alpha + \rho + \tau = 1 \]  

(3.1)

where

\[ \alpha: \text{Absorptivity} \]
\[ \rho: \text{Reflectivity} \]
\[ \tau: \text{Transmissivity} \]

The heat absorbed by the target material can be described by considering the Stefan-Boltzmann law and the radiation exchange between two surfaces. The heat transfer equation is following

\[ Q = FE\alpha k(T_s^4 - T_t^4) \]  

(3.2)

where

\[ Q: \text{Total heat transfer between source and target} \]
\[ F: \text{View factor between source and target} \]
\[ E: \text{Emissivity of the source} \]
\[ \alpha: \text{Absorptivity of the target} \]
\[ k: \text{Stefan-Boltzmann constant} \]
\[ T_s: \text{absolute temperature of source} \]
\[ T_t: \text{absolute temperature of target} \]

Thermoplastics are commonly considered as gray radiators. The reflected radiation from thermoplastic's surfaces in the infrared wavelength range is generally small compared to transmitted and absorbed irradiation by the material. In order to have a efficient heating, the peak power emission wavelength of the IR lamp must stay as close as
possible to the peak absorption wavelength of the polyethylene on the IR spectrum. Because the material used here has a very thin polyethylene coating on the shiny aluminum foil, the reflectivity in this case may be increased after the radiation penetrates the polyethylene layer and reflects back from the aluminum foil. But this may be beneficial for reheating the polyethylene layers. Also the transmissivity and absorptivity may vary depending on the temperature of both heat source and target material. According to the Wien’s displacement law, the temperature of heat source will affect the wavelength of emission.

\[ \lambda_p T = C_3 \]  

(3.3)

where

\[ \lambda_p \]: peak emission wavelength

\[ C_3 \]: the third radiation constant (\( C_3 = 2897.6 \mu m \cdot K \))

This means that the voltage of the power supply which can affect the temperature of the lamp can in turn affect the peak emission wavelength. Similarly, if the temperature of the target material is so high that it causes phase transformation in the material, variation in absorptivity of the radiation may occur. Furthermore, due to the inner reflections in crystalline structures, some of the penetrated radiation may be diffracted away to the outside of the irradiated body. Therefore, precise information regarding absorption condition of the material during the heating phase cannot be defined easily.

IR sealing process is like a further development of heated tool sealing substituting contacting heated tool with noncontacting radiant
lamp for the heat source. Same sealing processes are employed, two parts are brought in near the radiant lamp. After the surfaces have melted, the lamp is removed and the parts are pressed together. The sealing parameter are heating time, change over time, holding time, holding pressure. Change over time is the time period between removal of the lamp and the parts being pressed together. Therefore, in order to optimize the process, the change over time should be kept as short as possible to minimize the cooling of the parts before they are pressed together and meanwhile reduce the process time. One advantage of IR sealing over hot tool sealing is that there is no requirement for direct contact between the heat source and joint areas which prevents contamination. Compared to hot gas sealing, IR sealing offers the better control on the application of the heat energy and heating areas which make it a more efficient method. Moreover, IR can be a good replacement for laser sealing with much lower equipment and maintenance costs. Therefore, IR sealing excels hot gas, hot tool and laser sealing when considered for sealing of aseptic food packages. Based on this, IR sealing was selected for further study as a new sealing method to compare with the existing ultrasonic and induction sealing.

3.5.1 Experimental Procedures

A 1.1 KW Chromalox U-shape radiant heater was purchased as a heat source for the infrared sealing system. A computer controlled two-cylinder actuating system was built to control the sequential actions of
both heating and holding process (Figure 3.5; 3.6). The sample is cut into a 1 inch wide by 2 inch long rectangle as suggested in the ASTM peel test standard [23]. The radiant heater was surrounded by a aluminum pipe with two rectangular slim slots that can direct the IR light onto the samples. The heater was put as close to the samples as possible (approximately 1mm) to have efficient heating and a minimum change over time. The sequential actions and sealing parameters such as heat time and hold time were controlled through the actuating system by a PC compatible computer with data acquisition board and an interfacing device. The holding pressure were set to 240 and 480 psi for different heating times range from 0.5 to 1 seconds. The holding time and change over time were kept at 0.2 seconds. The interfacing device includes a ladder circuit and a relay driver which connects between the 110 volt switches and low voltage signals from data acquisition system (Figure 3.7; 3.8; 3.9). A software program was written for the data acquisition system to integrate the data acquisition system with interfacing device in order to allow the user to input the sealing parameters and record the actual values of these parameters (Appendix A). Figure 3.10 shows the flow chart of the software program. The holding pressure was controlled by adjusting the pressure regulator. Two samples were first heated by the radiant heater, after the heater was retracted by the first cylinder, the second cylinder brought the two heated samples together with a preset pressure, then the second cylinder was retracted and the process cycle is completed. Sealing parameters
C1: Cylinder # 1 -- deliver IR heater

C2: Cylinder # 2 -- deliver part

S1: Solenoid valve # 1 -- control cylinder # 1

S2: Solenoid valve # 2 -- control cylinder # 2

ls1: Limit switch # 1

ls2: Limit switch # 2

ls3: Limit switch # 3

ls4: Limit switch # 4

H: IR heater

Figure 3.5 Schematics of the computer controlled infrared sealing system
Figure 3.6 Photo of the computer controlled infrared sealing system
Figure 3.7 Ladder circuit -- controlled the sequential action of the solenoid valves
Figure 3.8 Relay driver which senses low voltage signal from DAS20 to activate the relay contacts in the ladder circuit
Figure 3.9 Connections inside the data acquisition system between the limit switches and relay contacts
Figure 3.10 Flow chart of the sequential controlled IR sealing
such as heating time, holding time and change over time were recorded when the sealing is completed.

In order to study the joint interface, the seal was cut and cold mounted. Then it was polished and examined microscopically. Some micrographs were taken to see the squeeze flow in the polyethylene layer and the damage to the aluminum foil.

3.5.2 Results and Discussion

Infrared sealing is a two step process. First step is the heating of the samples, then the samples are brought together with a preset holding pressure. Although a computer controls all the sequential actions, there still exists a change over time from 0.2 to 0.5 seconds depending on the travel time between the completion of heating and beginning of the sealing. During this period the heated samples are subjected to convective and conduction cooling. This creates a loss in the sealing efficiency because of the rapid cooling of the thin film. Figure 3.11 shows the effects of the sealing parameters on the peel strength. The heating time is the most critical sealing parameter to obtain a quality seal. Holding pressure has only a small effect on heating time. Low holding pressure is preferred over high holding pressure as long as the holding pressure is high enough to produce a quality seal. Figure 3.12 shows the micrograph of the joint interface of an IR sealed sample. The aluminum layers (two white lines at the center) are still intact. The duration of heating time depends on the power output of the radiant heater. In overall evaluation of the infrared sealing, the process time is longer than either ultrasonic or induction sealing but the seal quality is
Figure 3.11 Peel strength for infrared sealed samples of material A
Figure 3.12 Microscopic photo of IR sealed samples of material A (X50 magnification) 1.2s heating time 240 psi holding pressure
the same. Because of the long process time caused by the change over time, it is suggested that infrared sealing may be more suitable for continuous sealing such as shown in the laser sealing (Figure 3.4) rather than stepwise sealing in production line.

3.6 Ultrasonic Sealing

In ultrasonic sealing, low amplitude and high frequency sinusoidal vibrations are applied to the parts. It utilizes the vibrational energy to causes localized surface asperity deformation which is dissipated into heat due to viscoelastic heating and then melts the surface asperity to flow and fusion bond the parts. Figure 3.13 shows a typical schematic of ultrasonic sealing system. The converter is made of piezoelectric discs which convert electric signals or power from the power supply to mechanical vibration. A mechanical booster, which is connected to the converter, can change the amplitude of vibration by changing the area ratio. Between the booster and the parts is a horn which guides the vibrational energy to the parts. In order to efficiently transfer the vibrational energy onto the parts through the horn, the applied pressure on the parts is much higher than in other sealing processes.

Ultrasonic sealing is commonly classified into near-field and far-field sealing. Near field sealing is defined as the ultrasonic horn contacts the parts less than 6mm away from the joint interface. The amplitude of vibration at the joint interface is approximately equal to the vibration amplitude at the horn surface. In the case of sealing aseptic food
Figure 3.13 Schematics of a typical ultrasonic welding system
package the ultrasonic horn contacts the parts less than 2mm from the joint interface, therefore it is near-field sealing. Thus the attenuation of the ultrasonic motion caused by damping the amplitude of vibration is minimum.

Generally, there are four process parameters namely weld time, holding pressure, holding time, and amplitude of vibration. Larger holding pressure tends to decrease the weld time needed for melting to occur, yet the holding time is relatively steady. Amplitude of vibration can be varied by using different boosters. The amplitude of vibration affects the amount of energy dissipated in ultrasonic sealing and the stress experienced by the parts. Since the fast process time is the main concern, it is beneficial to use as high an amplitude of vibration as possible to decrease the weld time before the parts experienced excess damage caused by the high amplitude of vibration. Although ultrasonic sealing has been used in the food packaging industry for a long time, it is necessary to carry out some experiments in order to compare the sealing effectiveness with other methods.

3.6.1 Experimental Procedures

The ultrasonic sealing system used a 2KW, 20Khz Branson ultrasonic plastic welder model 900M. Figure 3.14 shows the experimental setup for ultrasonic sealing. The converter-booste-horn assembly which resides inside the welder is shown in Figure 3.15. This model is equipped with a microprocessor which can be used to collect the relevant information during welding, such as, weld time, holding time,
Figure 3.14 Photo of experimental setup for the ultrasonic sealing machine
Figure 3.15 Photo of a converter-Booster-horn assembly
holding pressure, energy input, and total collapse. A number of ultrasonic horns were prepared and tested for the sealing. A simple aluminum fixture was built to hold the sample during sealing. Sealing parameters, namely, weld time, hold time, and hold pressure can be set through the welding machine. Several amplitudes of vibration can be chosen by changing the booster (from 1 to 2.5 gain ratio). The holding pressure was varied from 1000 to 1750 psi for different weld time range from 0.6 to 0.18 seconds in order to find the optimal sealing conditions. Two types of material that manufactured by different company were used in the experiment. The structure and dimensions of the materials are appear to be the same, but the difference in material properties are not known. Only material B was sterilized by electron beam radiation. The size of the sample is the same as the one used in the IR sealing. In addition to peel tests, the seals were also examined microscopically.

3.6.2 Results and Discussion

3.6.2.1 Effect of sealing parameters on seal strength

Figure 3.16 and 3.17 show the effects of the sealing parameters on the peel strength for both materials. The cycle time (weld time + holding time) in order to get a quality seal is less than 0.2 second for both materials. A minimum holding time of 0.06 second was required for all weld times and holding pressures to provide sufficient cooling of the interface. For short weld times (weld time = cycle time-0.06), the energy input is not sufficient to have complete melting and results in incomplete
Figure 3.16 Peel strength for ultrasonically sealed samples of material A
Figure 3.17 Peel strength for ultrasonically sealed sample of material B
bonding and low peel strength. Both figures show that increasing seal time can improve the quality of seal until it reaches a peak value of peel strength, thereafter the peel strength will not increase regardless the increasing of the seal time. This is due to excess energy input to the interface and result in degradation of the PE and burned paper. Increasing the holding pressure can reduce the seal time without affecting peel strength until a critical holding pressure that squeezes out all the molten polyethylene in the joint interface. For material B, at 1250, 1500, 1750 psi pressure, the peel strength vary with the seal time in a similar trend. Therefore the critical holding pressure is around 1250 psi. Higher pressure than this does not help much in increasing the peel strength. For material A, only at 1500 and 1750 psi the peel strength vary with seal time in a similar trend. So the critical holding pressure is higher around 1500 psi. The average peel strengths for a good seal for materials A and B are around 8.5 lb/in and 8 lb/in respectively in which case the failure occurs at the paper cardboard.

3.6.2.2 Squeeze out of the polyethylene and breakage of the aluminum foil at the joint

Because of the high seal pressure in the ultrasonic sealing process, the aluminum foil usually breaks and is squeezed out along with the molten polyethylene layer. In addition to the static and dynamic compressive stress applied on the sample, there is a shear force which comes from the squeeze flow of the viscous molten polyethylene layer acting directly on the aluminum foil surface. If we consider the shear
force as the tensile force which applies on the small aluminum cross-section area, the resulting tensile stress can be higher than the tensile strength of the aluminum foil. The tensile stress resulting from the squeeze flow of the polyethylene are derived in the previous chapter. The comparison between the calculated tensile stress and tensile strength of aluminum foil will be made later to predict the breakage of the foil. In order to understand the discontinuities in aluminum before the squeeze flow become dominant, the static and dynamic compressive stresses must be taken into account. Based on the stress calculation, the static compression itself is not high enough to break the aluminum foil. This is also proved to be true in the experiment by applying the static pressure without ultrasonic vibration. On the other hand, the dynamic compression from the vibrating horn can cause some cracks to be initiated. It is found that even at 750 psi holding pressure (30 psi cylinder pressure) and 0.05 second weld time (ultrasonic vibration active), some small cracks are observed in the joint area where not much of the melting has yet occurred (Figure 3.18). As the pressure becomes higher, the number and size of the cracks increase (Figure 3.19 and 3.20). Based on the observations, we conclude that after the static pressure is applied to the sample, the dynamic pressure initiates some small cracks at the joint before the squeeze flow occurs. Once complete melting occurs, the shear force that comes from the squeeze flow of the molten polyethylene breaks the aluminum foil and squeezes it out with the molten polyethylene.
Figure 3.18 Crack in the aluminum foil at 750 psi and 0.05s weld time
Figure 3.19 More cracks in the aluminum foil at 1000 psi and 0.05 s weld time
Figure 3.20 Severe cracking of the aluminum foil at 2000 psi and 0.05s weld time
Figure 3.21 and 3.22 show the micrographs of the joint for different welding parameters. At low holding pressure and short seal time, the PE squeeze out and breakage of aluminum foil are minimal due to less melting and low holding pressure. As the holding pressure and weld time increase, the PE squeeze out and breakage of aluminum foil become pronounced. But the PE squeeze out and breakage of aluminum foil do not affect the peel strength. As a matter of fact, in ultrasonic sealing, a strong seal always experiences some PE squeezed out and breakage of aluminum foil.

3.7 Induction Sealing

Induction heating is widely used in the metal heating industry especially in the heat treatment of metals because of its ability to control the amount of heat input and to localize the area of heating with a high heating efficiency. Two mechanisms of energy dissipation are involved in inducting heating. These are energy dissipation due to joule heating by eddy current and energy dissipation associated with magnetic hysteresis [24]. Since nonmagnetic aluminum foil is used as the heating medium, the heating will be based on joule heating of the induced eddy current. Induction heating converts electrical energy into thermal energy by joule heating through conducting materials. An induction heating system usually has an AC power generator equipped with a tuning device and a working coil assembly. When an AC current passes through the working coil, a varying magnetic field is produced near the coil which, according
Figure 3.21 Microscopic photo of ultrasonically sealed samples of material A (x50 magnification) top: 0.1s heating time, 1000 psi bottom: 0.1s heating time, 1750 psi
Figure 3.22 Microscopic photo of ultrasonically sealed samples of material B (x50 magnification) top: 0.08s heating time, 1500 psi bottom: 0.1s heating time, 1750 psi
to Faraday's law, induces a voltage potential in the field. With a conducting material located in the field of induced voltage, joule heating will occur because there are induced eddy currents that pass through the conductor resulting in resistive loses. In this case, the joule heating occurs in the aluminum foil. The LDPE film next to the heated foil will heat up rapidly and eventually melt. A seal can be formed, when the two molten layers were pressed together. The amount of the heat dissipation by joule heating depends on the eddy current density and the resistivity of the aluminum foil. Since the LDPE film melts very rapidly, the coil design must not only try to maximize the eddy current intensity, but it also must produce uniform heating throughout the intended heating area to ensure a hermetic seal can be obtained in a minimum time.

Similar to ultrasonic sealing, there are three process parameters such as heating time, sealing pressure, and holding time. Since the power input is usually fixed at the maximum, controlling the heating time can control the amount of heating of the aluminum foil and heat transfer to the polyethylene layer. Usually the duration of heating is required to have sufficient melting along the whole seal line. The sealing pressure can be applied to the molten layers as soon as the heating begins. The pressure level should be kept low enough to prevent damage to the aluminum foil but high enough to ensure complete flow and diffusion at the joint interface. The holding of the parts after heating is completed is to resolidify the polyethylene and gives the seal strength.
3.7.1 Experimental Procedures

An ENI model EGR 1600B variable frequency (9 Khz-110Khz) power generator and a EIB-3A impedance matcher with an MT2 induction heating transformer are used to build the induction sealing system. A nonconductive fixture, which provides means of both holding and pressurizing the sample during the sealing process, was manufactured from Plexiglas. Induction coils were made with copper tube (1/8 inch diameter) through which the cooling water is passed during sealing. For efficient operation, the load impedance can be properly adjusted to match as closely as possible to the impedance of the generator. Frequency and power level of the power supply are adjusted simultaneously following the tune up procedures so as to obtain the most efficient power output. Same samples (1 inch wide by 2 inch long rectangle) as in IR and ultrasonic sealing were used in the induction sealing experiment. Since the aluminum foil is so thin that very few electromagnetic lines can pass through the foil in the longitudinal direction, the sample is aligned perpendicular to the axis of the coil in order to get the most uniform and efficient heating. Heating time is controlled by a remote switch connected to a computer based control system. Different heating time (0.2 to 0.4 seconds) under different holding pressure (7 psi and 15 psi) were used to find the optimal sealing conditions. The effects of different sealing conditions on the polyethylene layer and aluminum foil were evaluated by peel test and microscopic examination of the seal interface.
3.7.2 Results and Discussion

Unlike the ultrasonic sealing process, the most critical sealing parameter is heating time. There is only a slight relationship between the holding pressure and heating time (Figure 3.23). There does exist a minimum holding time of 0.1 seconds and a small holding pressure of 7 psi. Heating time varies with process power input and efficiency which depends on coil design and frequency adjustment. A process time of 0.3 seconds is needed to obtain a quality seal. For a specific power and frequency adjustment there corresponds an optimal heating time. Small holding pressure is preferred as long as a quality seal can be produced. One area that requires examining is the nonuniform heating pattern of the sample due to the edge effect of the induced eddy current. By examining the sealed sample that was peeled apart, there was fairly large melted region that spreaded along the longitudinal edges beside the top edge of the sample due to the edge effect. This unnecessary heating at the longitudinal edges lowers the heating efficiency of the sealing process. From the microscopic examination of the joint, there are no discontinuities in the aluminum foil and the polyethylene melt squeezed out is small (Figure 3.24). The average seal strength for material A. is also at 8 lb/inch in which case failure occurs at the cardboard.

3.8 Evaluation of Sealing Methods

A variety of heating techniques have been evaluated for speed and effectiveness in sealing aseptic packages. Table 3.2 shows a comparison of the sealing methods. In resistance sealing the problem of controlling
Figure 3.23 Peel Strength of inductively sealed samples of material A
Figure 3.24 Microscopic photo of inductively sealed samples of material A (X50 magnification) top: 0.3s heating time, 10 psi bottom: 0.4s heating time, 20 psi
Table 3.2

Comparison of the Sealing Methods

<table>
<thead>
<tr>
<th>Methods</th>
<th>Seal Quality</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance Sealing</td>
<td>N/A</td>
<td>Difficult to Prepare</td>
</tr>
<tr>
<td>Friction/Vibration</td>
<td>N/A</td>
<td>Difficult to prepare</td>
</tr>
<tr>
<td>Microwave/Dielectric</td>
<td>N/A</td>
<td>No Heating Effect</td>
</tr>
<tr>
<td>Hot Tool Sealing</td>
<td>good</td>
<td>Slow, Contamination</td>
</tr>
<tr>
<td>Hot Gas Sealing</td>
<td>good</td>
<td>Slow, low efficient heating</td>
</tr>
<tr>
<td>Laser Sealing</td>
<td>good</td>
<td>Fast, High Cost</td>
</tr>
<tr>
<td>IR Sealing</td>
<td>good</td>
<td>Slow</td>
</tr>
<tr>
<td>Ultrasonic Sealing</td>
<td>good</td>
<td>Fast, Breakage in Aluminum foil</td>
</tr>
<tr>
<td>Induction Sealing</td>
<td>good</td>
<td>Fast</td>
</tr>
</tbody>
</table>
the heating areas and creating direct contact between aluminum foil and the electrodes still exist. Friction and vibration sealing have difficulty in holding the packaging material. Microwave/dielectric sealing is not applicable because of the aluminum foil. Hot tool and hot gas sealing require a longer process time. The contamination problem by hot tool and the low heating efficiency by hot gas sealing put both methods at a disadvantage. YAG and CO₂ laser sealing produce excellent speed and quality sealing. But its high equipment and maintenance cost overshadow the advantages.

Three methods that are still outstanding are IR, ultrasonic and induction sealing. IR sealing, although it produces quality seals, the longer process time due to the change over time has lowered the competitiveness among the three methods. It is suggested that IR sealing is best used in a continuous sealing process like the side seam of the package instead of the final hermetic seal which requires change over time. Ultrasonic sealing is an effective sealing method. It has a short process time and high peel strength. But because it requires relatively high sealing pressures, the aluminum foil gets damaged and squeezed out along the seal. This presents a potential problem of breaking the barrier between the air and food and it may lead to the food spoilage. The final option left is induction sealing. Preliminary study shows that the speed and quality of the induction sealing are among the best. The main problem encountered in induction sealing is the nonuniform heating pattern in the 1 inch wide sample that is caused by edge effects. Although it does not affect the seal strength, it does consume some
energy on the area other than the top edge. Some studies showed that the edge effect can be lessened and a more uniform heating can be obtained by improving the coil design. Therefore, based on this evaluation, induction sealing was chosen for further in-depth study.
CHAPTER IV
OVERVIEW OF INDUCTION SEALING

4.1 Introduction

Electromagnetic induction heating, as its name implies, must have electrical currents that induced internally inside the conducting material to be heated. The induced eddy currents dissipate energy by joule heating. The uniqueness of the induction heating is that there is no external heating element but using the material to be heated as its own heating source. It also does not require any direct physical contact between the induction coil and the parts to be heated. Furthermore, it is possible to control the penetration depth or pattern by adjusting frequency, coil design, coupling, or power setting. All these features make induction heating an exceptional and efficient technique for some special heating applications.

Induction heating is commonly used in metal heating applications such as, heat treatment, welding, and melting. Table 4.1 shows some typical applications and products of induction heating. Nowadays the usage of the technique is greatly expanded due to the introduction of the concepts of the so called implant heating and sealing. As long as there is a heating agent (conducting medium) no matter if it is in form of powder or laminate, induction heating can be used to heat up the nonconducting
Table 4.1

Induction heating applications and typical products[24]

<table>
<thead>
<tr>
<th>Preheating prior to metalworking</th>
<th>Heat treating</th>
<th>Welding</th>
<th>Melting</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Forging</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gears</td>
<td>Surface Hardening, Tempering</td>
<td>Seam Welding</td>
<td>Air Melting of Steels</td>
</tr>
<tr>
<td>Shafts</td>
<td>Gears</td>
<td>Oil-country Ingot, tubular products</td>
<td></td>
</tr>
<tr>
<td>Hand tools</td>
<td>Shafts</td>
<td>Refrigeration tubing</td>
<td>Castings</td>
</tr>
<tr>
<td>Ordnance</td>
<td>Machine tools, Hand tools</td>
<td>Line pipe</td>
<td></td>
</tr>
<tr>
<td><strong>Extrusion</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural members</td>
<td>Through Hardening, Tempering</td>
<td></td>
<td>Vacuum Induction Melting</td>
</tr>
<tr>
<td>Shafts</td>
<td>Structural members</td>
<td></td>
<td>Ingots</td>
</tr>
<tr>
<td><strong>Heading</strong></td>
<td></td>
<td></td>
<td>Billets</td>
</tr>
<tr>
<td>Bolts</td>
<td>Through Hardening, Tempering</td>
<td></td>
<td>Castings</td>
</tr>
<tr>
<td>Other fasteners</td>
<td>Through Hardening, Tempering</td>
<td></td>
<td>“Clean” steels, Nickel-base</td>
</tr>
<tr>
<td><strong>Rolling</strong></td>
<td></td>
<td></td>
<td>superalloys</td>
</tr>
<tr>
<td>Slab</td>
<td>Annealing</td>
<td></td>
<td>Titanium alloys</td>
</tr>
<tr>
<td>Sheet (can, appliance, and automotive industries)</td>
<td>Annealing</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aluminum strip</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Steel strip</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
material next to the heating agent or even create a joint between two nonconductive parts. One of the areas that has successfully utilized the idea is the joining of thermoplastic parts. In order to join plastic parts together, it requires an electromagnetic active material as a heating agent. The heating agent is usually made by compounding ferromagnetic powder within a thermoplastic matrix which is compatible with the materials being joined. By using the special magnetically active material as a heating agent between two to be joined plastic parts, the parts next to the heating agent can be melted through conductive heat transfer and a joint can be created. If the heating agent is a thin metal layer or foil, it can be laminated into the plastic parts right underneath the layers to be joined such as in the paper/foil aseptic food packaging material. Once the thin conductive metal layer is heated up by joule heating, the polymer layer next to the metal will be melted and two molten polymer layers can be joined together.

Two mechanisms of energy dissipation are involved in induction heating. They are energy dissipation due to joule heating by eddy current and energy dissipation associated with magnetic hysteresis. In the case of sealing paper/foil aseptic food package, since non-magnetic aluminum foil is used as a heating medium, the heating will be based on joule heating due to the induced eddy current. When an alternating current passes through a coil it produces a changing magnetic field which, according to Faraday's law, induces a voltage in a conductor near the coil.

\[
\text{emf} = -N \frac{d\Phi}{dt}
\]  
(4.1)
where

\[ \text{emf: induced voltage} \]

\[ N : \text{number of turns in coil} \]

\[ \frac{d\phi}{dt} : \text{rate of changing magnetic flux} \]

With a conducting material which located in the field of induced voltage, there is induced eddy current passing through the material and it dissipates the energy by joule heating. The power dissipated by the eddy current can be calculated from Ohm's law:

\[ P = I^2 R \]  \hspace{1cm} (4.2)

where

\[ I : \text{induced eddy current} \]

\[ R : \text{equivalent resistance of the material} \]

The intensity of the joule heating depends on the eddy current density and resistivity of the aluminum foil. Since the resistivity of the foil cannot be controlled, the eddy current density has a major effect on the joule heating. The eddy current intensity depends on the coil current, frequency, geometry of the coil, and the coupling efficiency between the coil and the aluminum foil. A typical induction sealing system is composed of three basic components; namely,

1. AC Power Generator:

An AC power generator is capable of converting 60 Hz electrical power to KHz or even MHz range high frequency power. It is also required to output a high power to the coil/workpiece assembly in order to generate the heating in the workpiece. There are usually a
transformer and a tuning circuit along with the power generator which is capable of matching the impedance between the coil/workpiece assembly and the power generator.

2. Induction Coils:

The induction coils are connected to the output of the power generator directly or sometimes indirectly by putting a transformer in between. Because of the high conductivity of the copper, the coils are usually made of copper tubing which can be round, rectangular, or any special customer made shape. The diameter of the copper tubing varies a lot from less than 1/8 of an inch to more than an inch. The copper tubing is water-cooled. The coil should be designed in such a way that the heating pattern is uniformly distributed along the seal line. It is highly desirable to place the coil as close as possible to the heating agent to have a high coupling efficiency. A variety of coils can be used in induction heating applications. Figure 4.1 shows some typical coils that are frequently used in heating and sealing applications. The principles in choosing the right coil or designing the right coil are complicated due to the facts that many factors contribute to the coupling and heating efficiency. But the two things must be kept in mind when designing the coil are that the coil/workpiece should be able to be tuned with the power generator to get a maximum power output and the energy output is uniformly distributed in the desired heating area or volume.

3. Fixture:

A fixture can provide the appropriate support for the parts to be sealed and at the same time application of the desired pressure to insure
Figure 4.1 Some typical induction coils[24]
the intimate contact of two molten layers. The fixture should be made of nonconducting material such as plastics to avoid any reduction in the electromagnetic flux density in the heating agent. It usually incorporates a pneumatic press made of an air cylinder and a control valve to control the holding pressure and the holding time.

For the aseptic food package application, the transverse flux induction heating (sample is placed perpendicular to the magnetic flux outside the coil) was used instead of traditional axial flux alignment in which sample is placed parallel to the magnetic flux inside the coil (Figure 4.2). This was done because very little magnetic flux can pass through the very thin aluminum foil in the traditional axial flux alignment and result in less joule heating. Furthermore, when the sample is placed outside the coil, it is easier to apply the pressure while heating is taking place.

4.2 Literature Review

Since Michael Faraday discovered the electromagnetic induction technology in 1831, it was not until the latter half of the 19th century that the practical applications of induction heating of metal conductors was realized. The development of the high frequency power supply itself represents the evolution of the induction technology. Figure 4.3 show the variation in cost and efficiency of the power supply according to its own evolution. Although many researches have been conducted on induction heating or welding, the materials that are dealt with are mainly metals. It was not until the 1960's that bonding plastic by
Figure 4.2 (a) Traditional axial flux induction heating (b) transverse flux induction heating[25]
Figure 4.3 Conversion efficiency of induction heating power supplies - top; Change on cost of induction heating power supplies - bottom[24]
induction heating was introduced. Most of the researches on induction bonding of plastics are focused on the magnetic powder compounds that are compatible with thermoplastics. Both Chookazian and Leatherman [26];[27];[28];[29]have published several papers on this type of bonding of plastics. But their papers only addressed the practical uses of the induction bonding technique such as plastic bonding applications and improvement of bonding agent formulas.

Induction sealing is a complicated process, it can be divided into four subprocesses. These include 1) induction heating, 2) heat transfer, 3) squeeze flow, 4) diffusion. Each subprocess itself is a complicated process. Most of the papers like in Chookazian and Leatherman mainly emphasize the induction heating process. Although the induction sealing technique has been used in the food packaging industry for decades, no fundamental research has been done specifically on the induction sealing of the paper/foil aseptic food package. It was only mentioned as a sealing method for food packages in Aseptik 84 by Downes et al [13]. But on the other hand there are some technical papers available regarding the induction heating of aluminum strips. The idea of using transverse flux induction heating in non-ferrous metal strips was first proposed by Baker in 1950[30]. In this case the flux goes through the strip, instead of passing along it. He proved that this method is a practical and efficient way for heat treating of non-ferromagnetic strips like aluminum, brass, copper, etc. The idea was revived by Waggot et al [25] at the Electricity Council Research Center, Capenhurst in 1981. They successful designed
and built a 1 MW transverse flux inductor which is capable of continuously heat treating aluminum alloy strips at a speed of 2 m/s.
Heating is the most important process during sealing because it directly affects the process time and seal quality. Induction heating of paper/foil package material is a complicated process. It can be divided into two subprocesses, namely (1) Induction heat generation, (2) Heat transfer. In order to study the heating process of induction sealing, the two subprocesses will be modeled. Since the ANSYS finite element program is capable of handling both 3-D time harmonic electromagnetic and transient thermal problems, it was chosen to model the induction heating process[33]. There is no coupled field element type available for solving both 3-D harmonic electromagnetic and transient thermal problem at the same time. Therefore, the heat generation process was first modeled then the heat transfer process.

5.1 Induction Heat Generation

Two energy dissipation mechanisms are involved in induction heating generation. They are energy dissipation caused by joule heating when eddy currents are induced in a non-ferromagnetic conductor or energy dissipation due to magnetic hysteresis for a ferromagnetic conductor. Since the heating medium is aluminum foil which is a non-
ferromagnetic conductor, the energy dissipation is solely due to eddy current's joule heating. In order to determine the total heat generation in the package material, it is necessary to calculate the eddy current and power dissipation in the aluminum foil.

5.1.1 Formulations

An electromagnetic analysis is used to predict the eddy current distribution in the aluminum foil, from which the joule heating and temperature distribution are calculated. For a 3-D time harmonic electromagnetic analysis, the governing equation for eddy current prediction can be derived from Maxwell's equation.

\[ \nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J} \]  \hspace{2cm} (5.1)

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \]  \hspace{2cm} (5.2)

\[ \nabla \cdot \vec{B} = 0 \] \hspace{2cm} (5.3)

where

- \( \vec{H} \): magnetic field intensity
- \( \vec{B} \): magnetic flux density
- \( \vec{J} \): current density
- \( \vec{D} \): electric flux density
- \( \vec{E} \): electric field

The constitutive equations required are
\( \mathbf{J} = \sigma \mathbf{E} \quad (5.4) \)

\( \mathbf{B} = \mu \mathbf{H} \quad (5.5) \)

\( \mathbf{D} = \varepsilon \mathbf{E} \quad (5.6) \)

where

\( \sigma \) : electric conductivity

\( \mu \) : magnetic permeability

\( \varepsilon \) : electric permittivity

Since \( \nabla \cdot \mathbf{B} = 0 \) by defining a vector potential \( \mathbf{A} \) such that

\[ \mathbf{B} = \nabla \times \mathbf{A} \quad (5.7) \]

combining Eq 5.7 with 5.2 yields

\[ \nabla \times \mathbf{E} = -\nabla \times \frac{\partial \mathbf{A}}{\partial t} \quad (5.8) \]

which means

\[ \mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla \mathbf{V} \quad (5.9) \]

where \( \mathbf{V} \) is the electric scalar potential

combining Eq. 5.5 and 5.7 which gives

\[ \nabla \times \mathbf{H} = \nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} \quad (5.10) \]

Substituting Eq. 5.10 into Eq. 5.1 which gives

\[ \nabla \times \mathbf{H} = \nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J} \quad (5.11) \]
But for frequencies below MHz range $\frac{\partial \vec{D}}{\partial t}$ is small and can be neglected.

Therefore, Eq. 5.11 becomes

$$\nabla \times \left( \frac{1}{\mu} \nabla \times \vec{A} \right) = \vec{J}$$

(5.12)

By introducing the vector identity

$$\nabla \times \nabla \times \vec{A} = \nabla(\nabla \cdot \vec{A}) - \nabla \cdot \nabla \vec{A}$$

Eq. 5.11 becomes

$$-\nabla \cdot \left( \frac{1}{\mu} \nabla \vec{A} \right) + \nabla(\nabla \cdot \vec{A}) = \vec{J}$$

(5.13)

To ensure a unique vector potential solution a zero constraint $\nabla \cdot \vec{A} = 0$ is imposed on Eq 5.13. Then it becomes

$$-\nabla \cdot \left( \frac{1}{\mu} \nabla \vec{A} \right) = \vec{J}$$

(5.14)

By assuming there is no eddy current developed in the source element and combining Eq 5.4 ; Eq 5.9 with Eq 5.14, the final governing equation can be derived as

$$-\nabla \cdot \left( \frac{1}{\mu} \nabla \vec{A} \right) = -\sigma \frac{\partial \vec{A}}{\partial t} - \nabla V + \vec{J}_s$$

(5.15)

where $\vec{J}_s$ is the source current

For time harmonic analysis

$$\vec{J}_s = J_0 e^{i\omega t}$$

$$\vec{A} = A_0 e^{i\omega t}$$

where
$J_0$ : zero to peak amplitude of source current density
$A_0$ : zero to peak amplitude of nodal vector potential
$\omega$ : frequency
$t$ : time

Once the nodal vector potential inside the conducting medium (in this case aluminum foil) is found, the eddy currents induced in the conducting medium can be calculated as follows:

$$J_e = -i\omega\sigma A$$

where $J_e$ is the eddy current

The power dissipation due to the eddy current can be calculated from the electrical conductivity, frequency, and eddy current solution for the element comprising the conductor. The equation for power dissipation can be expressed as follows

$$P_{avg} = \frac{1}{2\sigma} \sum_{i=1}^{n} \left[ (J_{re}^i)^2 + (J_{im}^i)^2 \right] V^i \quad (5.16)$$

where

$P_{avg}$ : total average power dissipation
$J_{re}$ : real component of the eddy current
$J_{im}$ : imaginary component of the eddy current
$V^i$ : volume of each element

5.1.2 Implementation

In Figure 5.1, a flow chart is used to describe the process in the FEM electromagnetic analysis. Figure 5.2 shows the finite element mesh that was used in the electromagnetic analysis. The source current was applied
Figure 5.1 FEM electromagnetic analysis flow chart
Figure 5.2 Finite element mesh for electromagnetic analysis
to a 3.2 mm (1/8 inch) thick rectangular hollow block that represents the copper coil. The current in the coil was measured from the experimental setup and it was converted into the source current density for the input to the analysis. Surrounding the coil are elements with properties of air. The aluminum foil was placed underneath the block (coil) with a air gap in between.

Two boundary conditions were used in the electromagnetic analysis. Firstly, flux normal boundary condition is used to force the flux to flow normal to the surface to fulfill the transverse flux condition. Secondly, the far-field zero boundary condition is used to define where the field effects from the device being modeled are negligible. At this particular boundary the magnetic fields is assumed to be zero and thus the vector potential components are set to be zero \(A_x = A_y = A_z = 0\).

After the solution phase, there is some output data that is available for postprocessing. Available output data includes average vector potential components, forces, field intensity, flux density, applied source current density, eddy current density, and element geometry data. For our case the most important output data is the eddy current density which we can use to calculate the power dissipation during the postprocessing. A special ANSYS command program was written to calculate the RMS power dissipation in the aluminum foil during the postprocessing (Appendix B). It calculates the power dissipation for each element and then totals up the RMS power dissipation in the aluminum foil. Meanwhile, it opens an output file which contains a list of element
heat generation commands for the aluminum foil which can be later used as a heat input commands in an ANSYS thermal analysis.

The effects of temperature on electrical conductivity or (resistivity) were neglected because the conductivity can affect eddy current and joule heating in different ways. Higher conductivity will increase eddy current intensity. But on the other hand, higher conductivity will decrease the joule effect. Therefore, the overall effects from the variation of the conductivity on heating is small. In fact, by using a higher conductivity to consider the temperature effect, the difference of the final heat generation rate is within 5% of the one with room temperature.

5.2 Heat Transfer

FEM thermal analysis is used to study the heat transfer inside the package material. A 3-D isoparametric thermal solid element is used to calculate the temperature distribution for the package material during the sealing process. Figure 5.3 shows the flow chart of the FEM thermal analysis for this particular case. The FEM program for thermal analysis is listed in Appendix C. The temperature distribution for this element is obtained from the numerical solution of the following equation:

\[ \rho c_p \frac{\partial T}{\partial t} = k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \dot{q} \]  

(5.17)

where

\( \rho \): density

\( c_p \): specific heat

\( k \): thermal conductivity
Figure 5.3 FEM thermal analysis flow chart
\( q \): internal heat generation rate

The mesh geometry of the 3-D thermal analysis is built on the same geometry of the aluminum foil that is used in the electromagnetic analysis except that the coil and air are replaced by several layers of polyethylene and paperboard according to the cross-section of the package material in Figure 1.2. The overall dimension of the laminate mesh geometry is 2 inch (50.8 mm) long (X direction) 4 inch (101.6 mm) wide (Y direction) and 0.4 mm thick (Z direction). The file which contains the element heat generation commands for the aluminum foil from the electromagnetic analysis is copied into the thermal analysis program. These commands were used as a heat generation rate input for the thermal analysis. The convection heat loss was applied to the analysis during the cooling stage. The effects of temperature on physical properties of both aluminum and polyethylene were neglected because the variation from room temperature to 350 °C is small. After the solution phase, the temperature distribution and temperature history of the polyethylene layer next to the aluminum foil can be obtained and plotted.

One of the purposes of modeling the induction heating and heat transfer processes is that it can be used to aid in designing working coil. For example, by changing the air space inside the coil, the optimal air space can be determined without actually trying to make different size coils (see Figure 5.2). Too big or too small an air space results in lower heat generation rate in the aluminum foil. When the air space is too small the field of magnetic induction will be canceled, because the
opposite sides of the inductor are too close to each other. But when the air space is too big, the inductor on each side cannot fully add up and result in lower overall inductance. In order to find the optimal air space, several different air spaces were used to see its effects on the heat generation. By setting the air space to 15 mm, the temperature distribution of the polyethylene layer after 0.4 seconds of heating is shown in Figure 5.4. The highest temperature is at the center of the top edge which is 214 °C and decreasing towards the edges according to the heat generation input from electromagnetic analysis. The thermal contours are semi-elliptical in shape. For a small air space of 6 mm, the temperature distribution after the 0.4 seconds of heating is shown in Figure 5.5. The highest temperature is still at the center of the top edge but it is lower at 167 °C. After several trials, the optimal air space was found at 9 mm where the heating efficiency is much higher. Figure 5.6 shows the temperature distribution of the polyethylene layer after 0.25 second of heating. The pattern of the temperature distribution is pretty much similar, but the temperature is much higher for the optimal air space. Temperature history at three different locations (center, 2 cm from edge, and 1 cm from edge) are shown in Figure 5.7. The highest temperature point is when the heating stops at 0.25 second heating time then the temperature decreases as the cooling starts.
Figure 5.4 Temperature distribution for 0.4s heating time -- 15 mm air space
Figure 5.5 Temperature distribution for 0.4s heating time -- 6 mm air space
Figure 5.6 Temperature distribution for 0.25s heating time -- 9 mm air space
Figure 5.7 Predicted thermal history by FEM during induction sealing
CHAPTER VI
EXPERIMENTAL PROCEDURES

6.1 Construction of Induction Sealing System

Induction sealing of aseptic package requires a high frequency electromagnetic field to be generated in a coil and eddy current induced in the workpiece. In order to construct the induction sealing system, an ENI model EGR 1600B power generator, a MT2 matching transformer, and an EIB-3A coil assembly were used (Figure 6.1). Figure 6.2 shows the schematic of the induction system. The power generator is connected to the transformer by a coaxial cable. From the transformer, the high frequency signal is connected to the coil assembly where the high frequency current is generated. The power generator is capable of controlling the power up to 1.6 KW at a frequency from 9 KHz to 110 KHz. The matching transformer between the power generator and the coil assembly can be set to either step up or down in 1, 1.25, or 1.5 ratio. The coil is always cooled by passing cold water through the copper tubing.

The fixture for the induction sealing system is made of nonconductive plastic. Since the transverse flux induction heating is used, the central axis of the coil is perpendicular to the sample. Therefore, the pressure is applied along the axis down to the sample. A
Figure 6.1 Photo of the experimental setup of an induction sealing system
PG: 1.6 KW Power generator

TR: MT-2 Transformer (switchable taps)

CA: EIB-2 Coil assembly

coax: Coaxial wire connection

Figure 6.2 Schematics of the induction sealing system
small air cylinder is used to apply the pressure to the sample holding fixture during the sealing process. Figure 6.3 shows the actual fixture used for the induction sealing system. The whole fixture with the cylinder is clamped on a work table. The air cylinder is capable of producing forces up to 120 lb force and the cylinder pressure is controlled by a pressure regulator.

6.1.1 Tuning and Coil Design

Tuning is a very important procedure in order to get high efficiency heating. According to the maximum power transfer theory, the maximum power is transferred from a voltage source when the load impedance is equal to the conjugate of the source impedance. The load impedance is the impedance of the induction coil and the voltage source is transistor power generator. The purpose of matching is to transform the induction coil impedance to that of the generator and its coaxial cable (50 ohms). By adjusting the frequency of the power output and the transformer, the impedance of both the power generator and the coil assembly can be matched or tuned. Because different coils have different impedance at different frequencies, not all coils can be successfully tuned with the power generator i.e. the coil cannot produce high current output for this particular generator. Therefore some empirical rules should be used to do the preliminary coil design to figure out what types of coils can be tuned and produce the heating that is required for sealing aseptic food application i.e. a uniform 4 inch line heating across the top portion of the sample. A 1/8 inch copper tubing was used to make different shape coils.
Figure 6.3 Photo of the fixture for the induction sealing system
By trying out several coils, it was determined that the 5-6 turns rectangular shape coil can reach the prerequisite of both tuning and heating pattern. Then the final coil dimensions for most efficient heating of packaging material such as the air space between the top and bottom of the coil was determined by the FEM electromagnetic analysis. The final coil dimensions were 4 inch wide, 9 mm (0.354 inch) air space, and 51/2 turns rectangular coil. The 9 mm air space is the optimal distance according to the FEM electromagnetic analysis. The coil that was used in the experiment was wound as close as possible to the dimensions listed above. Different air space coils at 6 mm and 15 mm were also tried to see the heating effectiveness (Figure 6.4).

6.1.2 Data Acquisition System - Control Sealing Parameters and Measuring Temperature During Sealing Process

In order to control the amount of heating, the heating time of sealing process needs to be controlled. Also the temperature history of the sample at different locations during the sealing process needs to be measured to see the temperature variation along the seal line and to verify the prediction from the model. A Metrobyte DAS20 data acquisition system was used to control the heating time and at the same time, measures the temperature of the sample during the sealing process. By connecting a relay driver to the DAS20, the DAS20 can activate relay contacts to turn on or off the power generator according to the user defined heating time. For temperature measurement, in order to deal with the short process time and electromagnetic field interference a very
Figure 6.4 Different coils that are used in the experiment
fine K type thermocouple (Omega CHAL-001; 0.001 inch diameter) was used to measure the temperature of the molten PE layer during the sealing process. A 1 Khz frequency response amplification module (Analog device AD595AQ) was connected between the thermocouple and a computer based data acquisition system in order to amplify the measured temperature signal. A quick basic computer program was written to allow the user to input heating time, store the temperature signal from the amplification module and finally convert the signal into actual temperatures. The DAS20 computer program used in this application is different from other pure data collecting program, because it deals with two tasks at the same time. Since the controlling of the heating time and measuring of the temperature are happening at the same time, it is necessary to use the two different computer process units to deal with two different tasks at the same time. The control of the heating time is done with the computer CPU or so called foreground operation. On the other hand, the collecting of the temperature data is done by a direct memory transfer from the A/D to memory which is performed under the control of the IBM PC 8237 DMA controller without involving the CPU or so called background operation. Figure 6.5 shows the flow chart of the computer program. The computer program is listed in Appendix D.

6.2 Material Preparation

Two types of materials manufactured by different companies were used in the induction sealing experiment. Material B has been sterilized
Figure 6.5 Flow chart of the temperature collecting computer program
by EB irradiation. The structure of both materials are similarly laminated as LDPE/foil/LDPE/paperboard/LDPE but the variation in the properties are not given. Figure 6.6 shows the micrographs of the two different materials. The material was cut into a 4 inch x 2 inch rectangular sample. The samples were cleaned with water soaked lint free paper to prevent any contamination from dirt or dust.

6.3 Evaluation of Sealing Effectiveness under Different Sealing Conditions

The most important sealing parameter in the induction sealing case is the heating time because it controls the amount of heat input. Therefore it is desirable to study the effect of the heating time on the seal quality. Although it is suggested by previous study that the other sealing parameters like holding pressure and holding time are not as important as heating time to the seal quality, it is necessary to determine whether there is correlation between these parameters. Experiment suggests that holding time does not vary according to different sealing conditions. Therefore, the experiment plan concentrated on the variation of holding pressure and heating time. Three different holding pressures from 10 to 40 psi were used for each heating time in the sealing experiment. Four different heating time from 0.2 to 0.4 seconds were used in the experiment. In order to study the squeeze flow of the molten layer and breakage of the aluminum foil, some special sealing conditions were applied to see the effects of the extra-high holding pressure. The holding pressure was set from 40 to 280 psi with two different heating
Figure 6.6 Micrographs of the cross-section of an carton/foil aseptic food package material top: material A, bottom: material B
times at 0.3 and 0.4 seconds. These samples with special sealing conditions were later examined microscopically to see how the sealing parameters contributed to the squeeze flow of the molten layer and the breakage of the aluminum foil.

6.4 Testing and Evaluation of Seals

The two criteria which were used to evaluate the seals and the induction sealing process were process speed and seal quality. The ASTM F88-85 peel test was used to evaluate the strength of the seals[25]. Fin seal type geometry and test procedure were carefully followed. The tests were conducted on a Instron model 4201 tensile testing machine. The seals were also evaluated microscopically to study the melt squeeze flow and the damage to of the aluminum foil. The sealed samples were first cut into a 1 cm wide square. Then they were cold mounted on a sample holder and polished. Finally, micrographs for different sealing conditions were taken on the reflected light microscope.

6.5 Measurement of Coil Current and Power Output

Coil current was measured by using a F.W. Bell IHA-150 noncontact high frequency current sensor. An 15V DC power supply was connected to the sensor as an excitation voltage. By connecting the output from the sensor to an oscilloscope, it was possible to measure the peak-peak current in the coil. The power which dissipated by the coil at the specific power level was estimated by measuring the temperature rise during the
heating with no cooling water inside the coil. Neglecting the convection loss, the heat generation can be calculated by the following equation:

\[ Q = mC_p (\Delta T) \]

where

- \( Q \): heat generation in the coil
- \( m \): total mass of the coil (cooper tubing)
- \( C_p \): specific heat of the coil
- \( \Delta T \): temperature rise of the coil

the power dissipation in the coil can be calculated by dividing the heat generation by heating time. The total system power output was recorded directly from the power meter reading on the control panel during the sealing process.
7.1 Experimental Verification of Induction Heating and Heat Transfer Process Model

In order to verify the previously developed induction heating and heat transfer model, the comparison between the experimental results and predicted results from the developed model is necessary. Figure 7.1 shows the heating pattern of a sample with 0.25 heating time. As the picture shows, the most severe melting area is at the top center of the sample where the wrinkles occur. The semi-elliptical shaped thermal contours can be identified from the picture. Less severe melting occurs at the outer layer of the semi-elliptical contours. By comparing the actual heating pattern with the one from the FEM analysis prediction, it is found that the pattern of the temperature distribution is very similar. Note that at the top right and left 1/8 square inch area, the actual heating pattern does not experience melting at all. Whereas, in the predicted heating pattern, there are no such spots. In the making of the induction coil, it is impossible to wind a perfect rectangular shape coil unless it is made by casting. The four corners of the rectangular coil are inevitably curved. The two corners on the top contribute to the dead
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Figure 7.1 Heating Pattern of the sample using 9mm air space coil
spots in the actual heating pattern. The heating pattern concentrated on the top transverse edge and two top longitudinal edges near the corners can be explained by the so called edge effects. This is due to the fact that electromagnetic flux near the edges of a conducting media tends to concentrated at the edges.

The coils with different air spacing will have different heating effects. Figure 7.2 and 7.3 show the actual heating patterns for coil with different air spacing. By comparing the actual heating pattern and the predicted heating pattern for different air spacing, it is found that they are in good agreement. By observing the actual heating pattern of the samples, it is clear that both coils with either 15 mm or 6 mm air spacing have less heating than the coil with 9 mm air spacing. The results confirm the optimal air spacing that was predicted from the developed model.

In order to study the whole sealing process, it is necessary to measure the temperature history or thermal cycle, of the sample during the sealing process. Figure 7.4 shows the actual temperature history measured at three different location (center, 2 cm from edge, 1 cm from edge) on the sample during the sealing process with 0.25 heating time. The temperature reaches its peak right at the end of the heating and decreases as the cooling begins. As the thermal contours suggested, the temperature gets lower when it gets closer to the edge. By comparing the Figures 7.4 and 5.7(shown here again), it is found that the actual temperature history and predicted temperature history at different locations are in good agreement.
Figure 7.2 Heating Pattern of the sample using 6mm air space coil
Figure 7.3 Heating Pattern of the sample using 15mm air space coil
Figure 7.4 Temperature history measured from the experiment during induction sealing
7.2 Microscopic Evaluation of Seals and Validation of Squeeze Flow Analysis

Table 7.1 shows the calculated tensile stress acting on the aluminum foil under various sealing conditions for both induction and ultrasonic sealing. Although the pressure levels of the induction sealing have been deliberately elevated to higher pressures to study the squeeze flow, the resulting tensile stresses are still below the tensile strength of the aluminum foil. Figure 7.5 and 7.6 show the joint interface of the inductively sealed sample under different sealing parameters. At the same holding pressure, longer heating time tends to have more molten polyethylene squeeze out. Similarly, at the same heating time, the higher holding pressure tends to create more squeeze out of the polyethylene. But for all the pressure levels, the aluminum foil is still intact. On the other hand, the calculated tensile stresses acting on the aluminum foil for the ultrasonic sealing process were always higher than the tensile strength of the aluminum foil. Figure 7.7 and 7.8 shows the joint interface of the inductively sealed sample under extra high pressure condition. Figure 7.9 shows the joint interface of the ultrasonically sealed sample under different sealing conditions. As the pictures showed, as long as the melting occurs, the aluminum foil was broken and squeezed out along with the molten polyethylene. Therefore, under the optimal ultrasonic sealing conditions, the breakage of the aluminum foil is inevitable. Table 7.2 lists a comparison of the results from both model prediction and microscopic examination. It indicates that the simplified
Table 7.1

Calculated Resulting Tensile Stresses Acting on Aluminum Foil for Both Ultrasonic and Induction Sealing under Different Pressure Levels

<table>
<thead>
<tr>
<th>Pressure Levels</th>
<th>Tensile Stress</th>
<th>Tensile Strength of Al</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ultrasonic Sealing</td>
<td>Induction Sealing</td>
</tr>
<tr>
<td>92 psi</td>
<td>1.24 ksi</td>
<td>&lt; -- intact</td>
</tr>
<tr>
<td>185 psi</td>
<td>2.50 ksi</td>
<td>&lt; -- intact</td>
</tr>
<tr>
<td>231 psi</td>
<td>3.12 ksi</td>
<td>&lt; -- intact</td>
</tr>
<tr>
<td>277 psi</td>
<td>3.74 ksi</td>
<td>&lt; -- intact</td>
</tr>
<tr>
<td>1000 psi</td>
<td>43.18 ksi</td>
<td>&gt; -- break</td>
</tr>
<tr>
<td>1250 psi</td>
<td>53.97 ksi</td>
<td>&gt; -- break</td>
</tr>
<tr>
<td>1500 psi</td>
<td>64.77 ksi</td>
<td>&gt; -- break</td>
</tr>
<tr>
<td>1750 psi</td>
<td>75.57 ksi</td>
<td>&gt; -- break</td>
</tr>
</tbody>
</table>
Figure 7.5 Microscopic photo of inductively sealed samples material A (X50 magnification) top: 0.3s heating time, 10 psi bottom: 0.4s heating time, 20 psi
Figure 7.6 Microscopic photo of inductively sealed samples material B (X50 magnification) top: 0.2s heating time, 10 psi bottom: 0.2s heating time, 20 psi
Figure 7.7 Microscopic photo of inductively sealed samples using extra high pressure: 46, 92, 231 psi, 0.4s heating time (from top)
Figure 7.8 Microscopic photo of inductively sealed samples using extra high pressure: 92, 185, 276 psi, 0.3s heating time (from top)
Figure 7.9 Microscopic photo of ultrasonically sealed samples top: 0.1s weld time 1750 psi, Bottom: 0.13s weld time 1000 psi
Table 7.2

Comparison of the results from model prediction and microscopic examination for the aluminum foil breakage

<table>
<thead>
<tr>
<th>Pressure Levels</th>
<th>Model prediction</th>
<th>Microscopic examination</th>
</tr>
</thead>
<tbody>
<tr>
<td>U - Ultrasonic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I - Induction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I - 92 psi</td>
<td>intact</td>
<td>intact</td>
</tr>
<tr>
<td>I - 185 psi</td>
<td>intact</td>
<td>intact</td>
</tr>
<tr>
<td>I - 231 psi</td>
<td>intact</td>
<td>intact</td>
</tr>
<tr>
<td>I - 276 psi</td>
<td>intact</td>
<td>intact</td>
</tr>
<tr>
<td>U - 1000 psi</td>
<td>break</td>
<td>break</td>
</tr>
<tr>
<td>U - 1250 psi</td>
<td>break</td>
<td>break</td>
</tr>
<tr>
<td>U - 1500 psi</td>
<td>break</td>
<td>break</td>
</tr>
<tr>
<td>U - 1750 psi</td>
<td>break</td>
<td>break</td>
</tr>
</tbody>
</table>
7.3 Effect of Sealing Parameters on Seal Quality

Unlike the ultrasonic sealing process, the most critical sealing parameter is heating time because it controls the temperature of the polyethylene film. Figure 7.10 and 7.11 show that holding pressure has a small effect on peel strength and heating time for both materials. The holding pressure required to create acceptable seals is relatively low compared to ultrasonic sealing process. A process time of 0.3 seconds is needed to obtain a quality seal for both materials under optimal condition. Longer heating time tends to produce stronger seals until it reaches a peak peel strength where the most uniform melting occurs. After that, the excessive heating can only degrade polyethylene and burn the paperboard resulting in lower seal strengths. The average seal strengths of a seal for material A and B are around 7 lb/in and 8 lb/in respectively in which the failure occurs at the paper cardboard. By comparing the process time and seal quality of the material without the electron beam radiation sterilization with the material with the sterilization, it is found that there is no noticeable difference
Figure 7.10 Peel strength of inductively sealed samples of material A
Figure 7.11 Peel strength of inductively sealed samples of material B
CHAPTER VIII
CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

Sealing of paper/foil aseptic food package is a critical step in the manufacture of the package, because it directly affects the process speed and product quality. The sealing process can be divided into four important steps - 1. heating of the surface, 2. application of pressure, 3. intermolecular diffusion, 4. cooling. Both external and internal heating methods could be used to seal the package as long as they can melt the polyethylene layer efficiently. Some internal heating method such as ultrasonic sealing where heating energy is produced mechanically usually required much higher holding pressure during sealing process in order to induce the molecular vibration and friction at the joint interface. For semicrystalline polymer like polyethylene, intermolecular diffusion happens so fast once the temperature is above the melting temperature that the diffusion process presents no time delay compared with other processes and can be neglected when considering the whole process time.

A variety of possible heating methods for polyethylene film were evaluated. Among the eleven techniques, two of the existing techniques - ultrasonic and induction sealing and one new techniques - IR sealing
were regarded as most promising. In ultrasonic sealing, the vibrational energy induces viscoelastic heating at the joint interface and fusion bond the parts. Although it is a fast process, according to the microscopic examination, the aluminum foil underneath the polyethylene layer is always broken due to the high holding pressure that is required for ultrasonic sealing. This poses a problem of losing the gas barrier between the food and the environment. More biochemical studies are required to determined the effects of the breakage of the aluminum foil. For IR sealing, the electromagnetic wave carried thermal radiation energy is applied onto the material surface. Unlike the hot tool sealing, the IR sealing does not require any direct contact between the parts and heating element. But other than ultrasonic and induction sealing, the heating process and pressurizing process of the IR sealing is separated and an additional change over time is introduced. This put IR sealing process in a disadvantageous position. Induction sealing uses the joule effect in the aluminum foil that caused by the induced eddy current to heat up the polyethylene. It offers the fast process speed, strong peel strength, and no defects in the joint interface. Therefore, it was chosen for further study.

Heating and heat transfer during induction sealing of paper/foil aseptic food package were studied theoretically and experimentally. For induction heating modeling, a FEM time harmonic electromagnetic analysis is conducted to predict the power dissipation in the aluminum foil due to the induced eddy current. A set of heat generation rate command is generated by running the FEM electromagnetic program.
Then in the heat transfer modeling, a FEM transient thermal analysis is conducted to predict the temperature distribution and temperature history during sealing. The heat generation rate commands that were generated in the electromagnetic analysis was used as an heat input in the thermal analysis. The predicted temperature distribution and temperature history were verified experimentally. For squeeze flow analysis, a simplified 2-D Newtonian flow model was used to predict the amount of shear force caused by squeeze flow of the molten polyethylene. The shear force was considered as a tensile force acting on the thin aluminum foil. The calculated tensile stress caused by the squeeze flow for both induction and ultrasonic sealing were compared with the tensile strength of the aluminum foil to determine the occurrence of the breakage. The predicted results were verified by the microscopic examination of the joint interface.

Among sealing parameters, the heating time is the most important parameter to affect the peel strength and process time. Holding pressure and holding time are considered to be less influential to sealing process. Higher heating time is beneficial to the peel strength until it is overheated. Under the optimal sealing condition, the failure always occurs at the paperboard not at the joint interface. There is no noticeable effect of the electron beam radiation sterilization on the sealing process and quality.
8.2 Recommendations

As suggested in the previous chapter, IR sealing is more suitable for continuous sealing operation such as the side seam than the step-wise final hermetic seal for the aseptic food package. Two concepts are proposed for future research work on IR sealing. First, replacing non-focusable IR lamp with focused IR lamp Figure 8.1, to have a better understanding about the radiation and heating process. Second, using a continuous sealing process i.e. to move the sample while it is being heated and sealed instead of step-wise process. This continuous process can eliminate the change over time which exist in the previous two step process. Preliminary study with the FEM thermal analysis, it is determined that in order to obtain a uniform quasi-steady heating, the sample size must at least three times longer than the heat source (Figure 8.2). More experiments on this continuous mode IR sealing is required to study the effects of the sealing parameters on the process speed and seal quality.
Figure 8.1 Focus infrared lamp
Figure 8.2 Predicted peak temperature history of the moving heat source heated sample by FEM thermal analysis. Top: first 1/3 section of the sample; center: second 1/3 section of the sample; bottom: last 1/3 section of the sample.
REFERENCES


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5. Dickerson, R.W.; Read, R B. J. Dairy Sci. 1972, 56, 6-11B


19. Welding of polymer and polymeric composites class notes.


APPENDIX A

Computer Program for the Sequential Control of the IR Sealing Machine
Sequential Control for IR Sealing System

This program uses the digital input/output of das20 data acquisition system to control the sequential actions of the IR sealing system. Both heat time and hold time can be set through the program interactively. Actual heat time, hold time and change over time during the sealing are recorded.

Written by Hong-Jun yeh

--- INITIAL SCREEN PRE-AMBLE ---
SCREEN 0, 0, 0: WIDTH 80: CLS: KEY OFF

--- STEP 1: Load DAS20.BIN driver by contracting workspace ---
CLEAR, 49152!
DEF SEG = 0
SG = 256 * PEEK(&H511) + PEEK(&H510)
SG = SG + 49152! / 16
DEF SEG = SG
BLOAD "DAS20.BIN", 0

--- STEP 2: Initialize with mode 0 ---
DIM DIO%(10)
OPEN "DAS20.ADR" FOR INPUT AS #1
'get base I/O address
INPUT #1, BASE%
'base I/O address
DIO%(1) = 2
'D.M.A. level
DAS20 = 0
'call offset - always zero
FLAG% = 0
'error variable
MD% = 0
'mode 0 - initialize
CALL DAS20(MD%, DIO%(0), FLAG%)
IF FLAG% <> 0 THEN PRINT "INSTALLATION ERROR": STOP

Please check these following devices: 

- Turn on the air compressor
- Turn on the power for heater and control system
- Set heating time (sec)
- Set holding time (sec)
- Wait until temperature and pressure reach desired values

TA = TIMER
IF A$ = "ok" THEN GOTO 471 ELSE GOTO 460
MD% = 14
CALL DAS20(MD%, DIO%(0), FLAG%)
IF FLAG% <> 0 THEN PRINT "ERROR #": FLAG% "ON DIGITAL INPUT": STOP
149 IF DIO%(0) = 245 THEN GOTO 520 ELSE GOTO 471

474 MD% = 15
485 DIO%(0) = 1
490 CALL DAS20(MD%, DIO%(0), FLAG%)
500 IF FLAG% <> 0 THEN PRINT "ERROR # "; FLAG%; " ON DIGITAL OUTPUT"
510 ' READ DIGITAL INPUT TRIGGERED BY LS1
520 ' -----------------------------------------
530 PRINT "sol.1 is on"
540 MD% = 14
550 CALL DAS20(MD%, DIO%(0), FLAG%)
560 IF FLAG <> 0 THEN PRINT "ERROR # "; FLAGS; " ON DIGITAL INPUT": STOP
570 ' IF DIGITAL INPUT IS RIGHT SET TIMER TO CONTROL HEATING TIME
580 ' ----------------------------------------------------
590 IF DIO%(0) = 246 THEN GOTO 655 ELSE GOTO 590
600 ' WRITE DIGITAL OUTPUT TO TURN OFF THE SOLENOID 1
610 ' ----------------------------------------------------
620 T1 = TIMER
630 FOR I = 1 TO N
640 T2 = TIMER
650 T3 = T2 - T1
660 IF T3 > HEAT THEN I = N
670 NEXT
680 ' WRITE DIGITAL OUTPUT TO TURN OFF THE SOLENOID 1
690 ' ----------------------------------------------------
700 MD% = 15
710 DIO%(0) = 0
720 CALL DAS20(MD%, DIO%(0), FLAG%)
730 IF FLAG <> 0 THEN PRINT "ERROR # "; FLAG%; " ON DIGITAL OUTPUT"
740 ' READ DIGITAL INPUT TRIGGERED BY LS-2 : SOL-1 RETRACT
750 ' ----------------------------------------------------
760 ' WRITE DIGITAL OUTPUT TO TURN OFF THE SOLENOID 1
770 ' ----------------------------------------------------
780 MD% = 14
790 CALL DAS20(MD%, DIO%(0), FLAG%)
800 IF FLAG% <> 0 THEN PRINT "ERROR # "; FLAG%; " ON DIGITAL INPUT": STOP
810 IF DIO%(0) = 245 THEN GOTO 850 ELSE GOTO 780
820 ' WRITE DIGITAL OUTPUT TO TURN ON SOL-2 WHEN SOL-1 RETRACTED
830 ' ----------------------------------------------------
840 PRINT "HEATER RETRACTED, LS2 IS ON"
850 MD% = 15
860 DIO%(0) = 2
870 CALL DAS20(MD%, DIO%(0), FLAG%)
880 IF FLAG% <> 0 THEN PRINT "ERROR # "; FLAG%; " ON DIGITAL OUTPUT"
890 ' READ DIGITAL INPUT TRIGGERED BY LS-3 : SOL-2 IS IN HOLDING POSITION
900 ' ----------------------------------------------------
910 MD% = 14
920 CALL DAS20(MD%, DIO%(0), FLAG%)
930 ' WRITE DIGITAL OUTPUT TO TURN ON SOL-2 WHEN SOL-1 RETRACTED
940 ' ----------------------------------------------------
950 PRINT "SOL.2 IS ON, PRESSURIZING"
960 T4 = TIMER
N = 100000!
FOR I = 1 TO N
    T5 = TIMER
    T6 = T5 - T4
    IF T6 > HOLD THEN I = N
NEXT

'-----------------------------------------------------'------------------
'  WRITE DIGITAL OUTPUT TO RETRACT SOL-2 WHEN TIME IS REACHED
'  ----------------------------------------------------------------
MD% = 15
DIO%(0) = 0
CALL DAS20(MD%, DIO%(0), FLAG%)
IF FLAG% <> 0 THEN PRINT "ERROR # "; FLAG%; " ON DIGITAL OUTPUT"
PRINT "HOLDING ENDS, RETRACTING THE SOL.2"

'  READ DIGITAL INPUT TRIGGERED BY LS-4 WHEN SOL-2 RETRACTED
MD% = 14
CALL DAS20(MD%, D10%(0), FLAG%)
IF FLAG% <> 0 THEN PRINT "ERROR # "; FLAG%; " ON DIGITAL INPUT": STOP
IF DIO% (0) = 245 THEN GOTO 1150 ELSE GOTO 1080

'  WRITE DIGITAL OUTPUT TO TURN OFF POWER
MD% = 15
DIO%(0) = 4
CALL DAS20(MD%, D10%(0), FLAG%)
IF FLAG% <> 0 THEN PRINT "ERROR # "; FLAG%; " ON DIGITAL OUTPUT"
PRINT "TURN OFF THE POWER"
PRINT "ACTUAL HEATING TIME (sec) = "; T3
PRINT "ACTUAL HOLDING TIME (sec)"; T6
TC = T4 - T2
PRINT "ELAPSED TIME (sec) = "; TC
APENDIX B

FEM Electromagnetic Analysis Program to Calculate the Power Dissipation in the Aluminum Foil during Induction Heating
This program simulates the induction heating of a sterile food package. The input loading is the current density that is applied on the copper coil. The output is the element heat generation QE at the aluminum layer. The output QE can be used as a heat generation input for thermal analysis.

```
PREP7
/TITLE,INDUCTION SEALING OF FOOD PACKAGE - EDDY
CURRENT ANALYSIS
/com
/com file name: indpe15.dat (100Khz, 9mm air space, .06mm gap)
/com
/com This program simulate the induction heating of a sterile
/com food package. The input loading is the current density
/com that is applied on the copper coil. The output is the element
/com heat generation QE at the aluminum layer. The output QE
/com can be used as a heat generation input for thermal analysis.
/com
KAN,3
ET,1,96,2
KNL,1
NL,1,57,1
NL,2,55,1
NL,2,103,2.57E7
NL,2,157,2.57E7
NL,2,211,2.57E7
NL,3,55,1
NL,4,55,1
NL,5,55,1
NL,6,55,1
N,1
N,2,3.18E-3
N,5,12.18E-3
FILL
N,7,18.54E-3
FILL
N,10,50.8E-3
FILL
NGEN,2,10,1,10,,.001E-3
NGEN,2,10,11,20,,.018E-3
NGEN,2,10,21,30,,.06E-3
NGEN,2,10,31,40,,.21E-3
NGEN,2,50,1,50,,.3.18E-3
NGEN,5,50,51,100,,.24E-3
NGEN,2,50,251,300,,.3.18E-3
/COM
MAT,1
```
E,1,11,12,2,51,61,62,52 *MATERIAL 1 PE
EGEN,9,1,1
EGEN,6,50,1,9 *1-54
(COM
MAT,2
E,11,21,22,12,61,71,72,62 *MATERIAL 2 ALUMINUM
EGEN,9,1,55
EGEN,6,50,55,63 *55-108
(COM
MAT,1
E,21,31,32,22,71,81,82,72 * MATERIAL 1 AIR
EGEN,9,1,109
EGEN,6,50,109,117 *109-162
(COM
MAT,3
E,31,41,42,32,81,91,92,82 * MATERIAL 3 COPPER LEFT
EGEN,6,50,163,163 * 163-168
(COM
MAT,4
E,32,42,43,33,82,92,93,83 *MATERIAL 4 COPPER TOP
EGEN,3,1,169 *169-171
(COM
MAT,1
E,82,92,93,83,132,142,143,133 *MATERIAL 1 AIR INSIDE
EGEN,3,1,172
EGEN,4,50,172,174 *172-183
(COM
mat,6 *material 6 COPPER BOTTOM
e,282,292,293,283,332,342,343,333
egen,3,1,184 *184-186
(COM
MAT,5
E,35,45,46,36,85,95,96,86 *MATERIAL 5 COPPER RIGHT
EGEN,6,50,187,187 *187-192
(COM
mat,1 *material 1 air
e,36,46,47,37,86,96,97,87
EGEN,4,1,193
EGEN,6,50,193,196 *193-216
(PNUM,MNUM,1
/show,4107
/view,1,1,2,3
/com,eplot
/com NRSEL,X,0
NASEL,X,50.8E-3
/com NRSEL,Z,0
/com NASEL,Z,2.5E-3
/com NT,ALL,MAG,0
d,all,ux,0
NALL
KTEMP,-1
KBC,1
ERSEL,MAT,3  *LEFT
TE,ALL,,4000000
eall
ERSEL,MAT,4  *TOP
TE,ALL,-4000000
eall
ersel,mat,6
te,all,4000000  *BOTTOM
eall
ERSEL,MAT,5
TE,ALL,-4000000  *RIGHT
EALL
HARFQ,100000
ITER,1,0,1
WSORT,X
AFWRIT
FINISH
/EXE
/INPUT,27
FINISH
/POST1
COND=2.57E7
LCLIM,3
STRES,J,96,61
STRES,VOLU
LCASE,1
SET,1,1
ESEL,MAT,2
SMULT,J2,J,J
SADD,Q,J2,,(1/(2*COND))
SMULT,PAVG,Q,VOLU
LCASE,2
SET,1,1,,1
SMULT,J2,J,J
SADD,Q,J2.,(1/(2*COND))
SMULT,PAVG,Q,VOLU
LCADD,3,1,2
LCASE,3
*GET,ELE,ELMN
*CFOPEN,HEATGEN
:LOOP
*GET,VAL,Q,ELE
*CFWRIT,QE,ELE,VAL
*GET,ELE,ELMN,ELE
*IF,ELE,NE,0,:LOOP
*CFCLOS
PRSTRS,J,Q,PAVG
SSUM
*GET,P,SSUM,PAVG
*STAT
FINISH
APPENDIX C

FEM Thermal Analysis Program to Calculate the Temperature Distribution at the Polyethylene Layer During the Sealing
/COM, ANSYS REVISION 4.4 UP437 A 16 23.7162
/PREP7
/TITLE, INDUCTION HEATING OF ASEPTIC FOOD PACKAGE- THERMAL ANALYSIS
/com
/com file name: indthe.dat (100KHz, 9mm space, .06mm gap, 1sec)
/com
/com This program use the QE commands obtained from eddy current
/com analysis as a load input and do a heat transfer analysis for the food
/com package material. The Q input is at aluminum layer. The
/com temperature at the PE layer is predicted.
/com
KAN,-1
ET,1,70
KXX,1,0.33  * PE CONDUCTIVITY
KXX,2,237   * AL
KXX,3,0.33   * ADH
KXX,4,0.15   * PAPER
KXX,5,0.33   * PE
/com
/com
DENS,1,910  * DENSITY
DENS,2,2702
DENS,3,910
DENS,4,160
DENS,5,910
/com
/com
C,1,2315   * SPECIFIC HEAT
C,2,830
C,3,2315
C,4,1200
C,5,2315
/com
/com node generation
/com
N,1
N,2,3.18E-3
N,5,12.18E-3
FILL
N,7,18.54E-3  * NODE 7
FILL
N,10,50.8E-3
FILL
NGEN,2,10,1,10,,,,0.054E-3 *PE
NGEN,2,10,11,20,,,,0.018E-3 *AL
NGEN,2,10,21,30,,,,0.006E-3 *ADH
NGEN,2,10,31,40,,,,0.27E-3 *PAPER
NGEN,2,10,41,50,,,,0.02E-3 *PE
NGEN,2,60,1,60,,,,3.18E-3
NGEN,5,60,61,120,,,,24E-3
NGEN,2,60,301,360,,,,3.18E-3
/COM
/COM ELEMENT GENERATION
/COM
MAT,1 *PE
E,1,11,12,2,61,71,72,62
EGEN,9,1,1
EGEN,6,60,1,9 *1-54
MAT,2 *AL
E,11,21,22,12,71,81,82,72
EGEN,9,1,55
EGEN,6,60,55,63 *55-108
MAT,3 *ADH
E,21,31,32,22,81,91,92,82
EGEN,9,1,109
EGEN,6,60,109,117 *109-162
MAT,4 *PAPER
E,31,41,42,32,91,101,102,92
EGEN,9,1,163
EGEN,6,60,163,171 *163-216
MAT,5 *Pe
E,41,51,52,42,101,111,112,102
EGEN,9,1,217
EGEN,6,60,217,225 *217-270
/SHOW,4107a
/VIEW,1,1,2,3
/com E PLOT
tunif,23
/COM
/COM INPUT LOADING
/COM
ITER,10,0,1
time,,25
KTEMP,-1
KBC,1
QE,55,0.1920077E+10
QE,56,0.5477483E+10
QE,57,0.7639063E+10
QE,58,0.6849621E+10
QE,59,0.3807467E+10
QE,60,0.1447011E+10
QE,61,0.1814439E+09
QE,62,4684860
QE,63,156677
QE,64,0.1649231E+11
QE,65,0.6709735E+10
QE,66,0.1233517E+10
QE,67,0.1911531E+10
QE,68,0.4489883E+10
QE,69,0.3122553E+10
QE,70,0.6049708E+09
QE,71,0.2876839E+08
QE,72,1934017
QE,73,0.1925202E+11
QE,74,0.8037575E+10
QE,75,0.1111749E+10
QE,76,0.1273796E+10
QE,77,0.4073491E+10
QE,78,0.3087478E+10
QE,79,0.7171127E+09
QE,80,0.5250507E+08
QE,81,0.1315927E+08
QE,82,0.1925202E+11
QE,83,0.8037575E+10
QE,84,0.1111749E+10
QE,85,0.1273796E+10
QE,86,0.4073491E+10
QE,87,0.3087478E+10
QE,88,0.7171127E+09
QE,89,0.5250507E+08
QE,90,0.1315927E+08
QE,91,0.1649231E+11
QE,92,0.6709735E+10
QE,93,0.1233517E+10
QE,94,0.1911531E+10
QE,95,0.4489883E+10
QE,96,0.3122553E+10
QE,97,0.6049708E+09
QE, 98, 0.2876839E+08
QE, 99, 1934017
QE, 100, 0.1920077E+10
QE, 101, 0.5477483E+10
QE, 102, 0.7639063E+10
QE, 103, 0.6849621E+10
QE, 104, 0.3807467E+10
QE, 105, 0.1447011E+10
QE, 106, 0.1814439E+09
QE, 107, 4684860
QE, 108, 156677
LWRITE *load step 1
QDELE, ALL
ITER, 1, 0, 1
TIME, 0.2501
LWRITE *load step 2
KBC, 1
EC, 1, 5, 60, 25, 54, 1
EC, 216, 3, 60, 25, 270, 1
ITER, 25, 0, 1
TIME, 0.5001
LWRITE *load step 3
KBC, 1
EC, 1, 5, 40, 25, 54, 1
EC, 216, 3, 40, 25, 270, 1
ITER, 25, 0, 1
TIME, 1.0001
LWRITE *load step 4
EC, 1, 5, 30, 25, 54, 1
EC, 216, 3, 30, 25, 270, 1
ITER, 20, 0, 1
TIME, 2
LWRITE *load step 5
EC, 1, 5, 7, 25, 54, 1
EC, 216, 3, 7, 25, 270, 1
ITER, 10, 0, 1
TIME, 5
LWRITE *load step 6
AFWRITE
FINISH
/EXEC
/INPUT, 27
FINISH
APPENDIX D

Computer Program for the DAS20 Data Acquisition System to Measure the Temperature During the Induction Sealing Process
This program `bind.bas` controls the heating time of the induction sealing machine. Meanwhile, it measures the power output from the machine and the temperature of the sample during the sealing.

written by Hong-Jun Yeh 10/28/92 DAS20

```
DIM dio%(10)
DIM DT%(2000), CH%(2000) 'set up integer arrays for data/channel #

COMMON SHARED dio%(), DT%(), CH()
DECLARE SUB DAS20 (MODE%, BYVAL dummy%, FLAG%)

'$DYNAMIC
DIM dat%(2000)
'$STATIC

'-------- Initialize section -------------------------------
SCREEN 0, 0, 0: CLS : KEY OFF: WIDTH 80

200 '------ STEP 2: Initialize with mode 0 -------------------
210 ' OPEN "DAS20.ADR" FOR INPUT AS #1 'get base I/O address
220 INPUT #1, dio%(0)
230 CLOSE #1
240 dio%(1) = 2 'interrupt level
250 dio%(2) = 1 'D.M.A. level
270 FLAG% = 0 'error variable
280 MD% = 0 'mode 0 - initialize
290 CALL DAS20(MD%, VARPTR(dio%(0)), FLAG%)
300 IF FLAG% <> 0 THEN PRINT "INSTALLATION ERROR": STOP'Halt on error
304 ' ' ----- Set output to "0" before operation
306 ' MD% = 15
307 dio%(0) = 0
308 CALL DAS20(MD%, VARPTR(dio%(0)), FLAG%)
310 IF FLAG% = 0 THEN PRINT "ERROR # "; FLAG% "ON DIGITAL OUTPUT"
314 ' '----------------- STEP 3 -------------------------------
316 'Set programmable timer to output desired sample rate
317 ' SAMPLE RATE = 5,000,000 / (DIO%(0) * DIO%(1))
319 ' NOTE: if DIO%(1) is 0 then only 16 bits of counter is used
321 ' and SAMPLE RATE=5,000,000/dio%(0)
322 ' di0%(0) = 5000 'sample at 200 samples/sec
324 di0%(1) = 10
```
MD% = 24 'adc pacer timer set mode
CALL DAS20(MD%, VARPTR(dio%(0)), FLAG%)
IF FLAG% <> 0 THEN PRINT "Error in setting timer. Error #"; FLAG%; STOP

'----- STEP 4: Prompt for scan sequence and set using mode 1 ---------------

'----- Channel 0 -- temperature measurement -----------------------------

dio%(0) = 3 'set channel -- "0"
dio%(1) = 0 'set gain range (0-10V) -- "0"
dio%(2) = 1 'first entry -- "2"
MD% = 1 'mode 1 - set scan sequence
CALL DAS20(MD%, VARPTR(dio%(0)), FLAG%)
IF FLAG% <> 0 THEN PRINT "Error #"; FLAG%; " in setting scan sequence": STOP

Channel 3 -- Power measurement ------------------------------------------

dio%(0) = 3 'set channel -- "3"
dio%(1) = 0 'set gain range (0-10V) -- "0"
dio%(2) = 1 'last entry -- "1"

CALL DAS20(MD%, VARPTR(dio%(0)), FLAG%)
IF FLAG% <> 0 THEN PRINT "Error #"; FLAG%; " in setting scan sequence": STOP

'----- Ready to start the heating process --------------------------------

INPUT "***** SET HEATING TIME (SEC)"; HEAT
PRINT
INPUT "***** TYPE y WHEN YOU ARE READY TO START, THEN HIT RETURN"; A$
IF A$ = "y" OR A$ = "Y" THEN GOTO 704 ELSE GOTO 608

'----- STEP 6 Start the heating process -----------------------------------

T1 = TIMER
M = 100000
FOR I = 1 TO M
T2 = TIMER
T3 = T2 - T1
IF T3 > 3.5 THEN I = M
NEXT

Set digital output D04 to Hi and close the N.O. #5 contacts to start

MD% = 15
dio%(0) = 16
CALL DAS20(MD%, VARPTR(dio%(0)), FLAG%)
IF FLAG% <> 0 THEN PRINT "ON DIGITAL OUTPUT"

T4 = TIMER
M = 100000
FOR I = 1 TO M
T5 = TIMER
T6 = T5 - T4
IF T6 >= HEAT THEN GOTO 740
NEXT

Set digital output to "0" to stop the heating process ----------------------

MD% = 15
dio%(0) = 0
CALL DAS20(MD%, VARPTR(dio%(0)), FLAG%)
IF FLAG% <> 0 THEN PRINT "ON DIGITAL OUTPUT"

'----- STEP 5 D.M.A. A/D conversions -------------------------------------

'Now set A/D conversions and D.M.A. going using mode 6
dio%(0) = 2000  'Total number of conversions
747 dio%(1) = VARSEG(dat%(0))  'Memory segment to dump data
748 ' 'Change this to suit your system.
749 dio%(2) = 2  '0 = trigger external
750 ' '1 internal pace , external gate
751 ' '2 internal pace start NOW
752 ' 'Try 0 with an external pulse generator to IP0
753 dio%(3) = 0  '0 = One shot and finish
754 ' '1 = Continuous scanning
755 MD% = 6  'mode 6 - A/D conversions using D.M.A.
756 CALL DAS20(MD%, VARPTR(dio%(0)), FLAG%)  'set it going
757 IF FLAG% <> 0 THEN PRINT "Error in mode 6 setup = "; FLAG%; STOP
758 ' 'Set N = Total number of conversions requested
760 N = dio%(0)
762 T7 = TIMER
764 M = 100000
765 FOR I = 1 TO M
766 T8 = TIMER
767 T9 = T8 - T7
769 NEXT
771 '------ STEP 7 Data transfer to basic array ------------------------------------
773 'Retrieve data to arrays DT%(*) and CH%(*) using mode 13
774 'number of words to transfer
775 dio%(0) = N
776 dio%(1) = VARSEG(dat%(0))  'memory segment to transfer from
778 dio%(2) = 0  'start transferring at conversion 0
779 dio%(3) = VARPTR(DT%(0))  'location of DT%(*) array
780 dio%(4) = VARPTR(CH%(0))  'location of CH%(*) array
782 MD% = 13  'mode 13 - data transfer
784 CALL DAS20(MD%, VARPTR(dio%(0)), FLAG%)  'make transfer
786 IF FLAG% <> 0 THEN PRINT "Mode 13 data transfer error # "; FLAG%; STOP
788 '------ STEP 8 Save the results ---------------------------------------------
790 OPEN "C:\tdas20\TEMP.DAT" FOR OUTPUT AS #1
792 FOR I = 0 TO (N - 1)
793 Y = DT%(I) / 4095 * 10  'Actual voltage from the temp. amp. module
794 X = (Y / 247.3) - .000011  'Transfer to K type mv
795 Z = X * (67233.42479# + X * W) + Z
797 W = 24512.109# + Z
799 T = .226584602# + X * W
801 M = I + 1
803 PRINT #1, M, T
805 NEXT I
807 CLOSE #1
810 'OPEN "C:\TDAS20\POWER.DAT" FOR OUTPUT AS #2
812 FOR I = 1 TO (N - 1) STEP 2
814 P = DT%(I) / 4095 * 10
816 J = (I + 1) / 2
818 'PRINT #2, J, P
820 'NEXT I
822 'CLOSE #2
824 '------ STEP 9 End D.M.A. operation ------------------------------------------
826 'End D.M.A. operation using mode 11 - strictly only needed in recycle mode.
828 'This step is not needed if in one shot (non-recycle) mode as the
829 'D.M.A will terminate automatically on completion of conversions.
830 MD% = 11
832 CALL DAS20(MD%, VARPTR(dio%(0)), FLAG%)  'do it
834 END