The closure process for packaging is a key process. It ensures the protective function of packaging and assures the packaged goods a long life. In this context, efficient and reliable sealing processes are essential for the production of sustainable packages.

In this paper, several characteristics of the ultrasonic sealing process will be discussed and accompanied by experimental results. The introduction provides an insight into the ultrasonic sealing process, its heating mechanisms and the process steps. A comparison is made with conduction sealing. Furthermore, basic principles of heating and energy dissipation are related to the influences of the sealing parameters on the seam strength. The experimental studies were carried out on typical packaging films, such as polyamide-polyethylene laminates. The seam strength in ultrasonic sealing is compared with that in conductive sealing. A lower seam strength was found for ultrasonic sealing in all the tested films. Furthermore, the sealing behaviour of the packaging films contaminated with different kinds of foods was analysed for both sealing methods. Although the ultrasonic sealing method has marginal advantages for bulk materials such as wheat flour, conduction sealing was shown to be better for other products. A comparison of the energy consumption during the ultrasonic and conduction sealing verified the advantages of ultrasonic sealing. In particular for thick packaging films, the amount of energy required for bonding is significantly lower than for conduction sealing.

In summary, this paper provides a survey of the characteristics of the ultrasonic sealing method in packaging applications – its advantages and limitations. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: ultrasonic sealing; sealing methods; energy efficiency of sealing processes

INTRODUCTION

The sealing equipment

Different sealing methods are used in packaging processes, such as conduction sealing, high frequency sealing and ultrasonic sealing. Conduction sealing is one of the conventional sealing methods for packaging; it is applicable for lots of packages and packaging materials. High frequency sealing technique, however, is only suited for polar materials for dielectric sealing such as polyvinylchloride or need metallic component such as aluminium for induction sealing. Many studies have been carried out about the sealing behaviour of different packaging material, the influence of sealing parameters and the influence of sealing jaw profiling on seam strength for conduction sealing. Ultrasonic sealing processes have been little used for packaging applications compared with the established sealing methods. In the past, this method was only used for special applications such as for the closure of beverage cartons. Research in the field of ultrasonic sealing was very rare except the studies of ERNST. He already analysed the sealing behaviour of different packaging films, also peel able films. However, in
recent years, the ultrasonic sealing method has been increasingly used for flexible packaging. Currently, there are different applications in bag form fill seal (FFS) and fill and seal machines that utilise the ultrasonic sealing method. Ultrasonic welding is an established and well-known method for joining polymers. This method of welding plastic parts has comparatively short welding times. During ultrasonic welding, the polymer parts or films get compressed and oscillated by longitudinal vibrations of the tool, the horn. A high frequency electrical field is converted into a mechanical oscillation within the so-called converter, typically made up of piezoelectric transducers. Typical frequencies for ultrasonic welding are 20, 30, 35 and 40kHz. The amplitude of the converter is transformed by a mechanical booster. Additionally, the oscillation is transformed and transferred to the welding parts or films by the horn (Figure 1b).

Amplitudes used for plastic welding are in a range of 25–60μm. For the sealing of thin packaging films, amplitudes of 10–30μm are usually used, depending on the film properties and equipment set-up. To ensure the transmission of the ultrasonic vibrations and energy dissipation, the horn presses the films against a counter tool, which is called the anvil. In the case of ultrasonic sealing of films, the anvil additionally has the function of an energy director. For ultrasonic welding, energy directors are necessary to concentrate the ultrasonic energy. The special shape of the energy directors leads to strain in the fusion zone, which leads to local well-defined heating and melting. It is also possible to integrate the energy director into the horn. Several kinds of shapes can be used as energy directors. Simple line structures are often used for pouch sealing. These are small profiled line bars with different radii, meaning ultrasonic sealed seams typically have a width of only 1–3mm. For applications for which the appearance of the seam is important, it is also possible to add the so-called cosmetic features to broaden the seam. In contrast to conduction sealing where the heat is transferred directly by the heated sealing jaw in ultrasonic sealing, the required heat for melting and bonding is dissipated within the material itself. The resulting temperature profiles for both methods are schematically illustrated in Figure 2 where the different curves represent different points in time (proceeding sealing time).

For conduction sealing, the configuration is much simpler (Figure 1a). The heat-sealing device consists of two sealing jaws that are heated by heating cartridges. The heat-sealing jaws and the resulting seams are often wider than ultrasonically sealed seams and are also often shaped or rifled to improve the seam quality. In the process cycle for a non-continuous sealing process, the heat transfer starts immediately when the tools are closed and ends when the tools are opened again. In ultrasonic sealing, the heating is initiated by starting the vibration of the horn. Additionally, the horn has to be charged with force to ensure the transmission of the vibration to the films. The heat generation is stopped by switching off the ultrasound. The seam may then be able to cool down in contact with the cool tools. This is not possible for conduction sealing with permanently heated sealing jaws. In addition to the intermittent process cycle, which is typically used in transversal sealing units with box motion or long-dwell principle, it is also possible to run the process continuously with rotating tools, even for ultrasonic sealing. For continuous longitudinal seam sealing in vertical or horizontal form fill seal machines, stationary tool can also be used. Here, the film is pulled through the gap between the oscillating horn and the anvil. In this case, it is necessary to have an amplitude magnitude which allows a periodic release of the films to avoid wrinkling. Ultrasonic sealing has particular advantages for
longitudinal seam sealing in horizontal form-filling and sealing machines for confectionary products such as chocolate. The cool tools prevent melting of the product during downtimes, which helps to reduce rejections. In this context, the ultrasonic sealing method may be a useful alternative to cold sealing processes and help reduce costs for packaging materials.

Mechanisms of energy dissipation and bonding

The heating mechanism for the ultrasonic welding of thermoplastic polymers has been discussed in various publications.\[^9\]–\[^11\],\[^14\] In general, a distinction is made between heating because of intermolecular friction and heating due to interfacial friction. The real bonding process is then induced by intermolecular diffusion processes,\[^11\] which require heat to enable molecular motion and entanglements. Chemical reactions during the ultrasonic welding of thermoplastics have been detected,\[^12\] but in other studies\[^13\] are estimated to be less important, not responsible for bonding and caused by degradation because of the heat. Potente\[^11\] argued that either intermolecular or combined intermolecular and interfacial friction occurs. Additionally, he predicated that the interfacial friction stops when a critical welding force is achieved. He also defined a dimensionless characteristic for ultrasonic weld ability depending on the welding pressure and the polymers’ viscoelastic properties. Ritter\[^14\] verified that interfacial friction is nearly independent of the static welding pressure and is a result of asymmetric construction. In a study on the heating behaviour of polymer films by Bach,\[^15\] both energy dissipation mechanisms were detected.

Both mechanisms occur together but with different intensity. Significant heating because of interfacial friction as shown in Figure 3 (left) was detected only for stiff material with a Young’s modulus greater than 1000MPa, such as polyethylene high-density. More typical for the often softer sealing layers of laminated packaging films is the heating behaviour shown in Figure 3 (right) where heating because of inter molecular friction dominates.

It was also found\[^10\] that heating because of interfacial friction in stiff material only occurs within the first milliseconds of the process and does not significantly speed up the heating process. Comparison of polyethylene low-density with a Young’s modulus of about 400MPa and polyethylene high-density with a Young’s modulus of about 1200MPa showed that nearly the same temperature level was reached for both materials in a defined sealing time under the same process conditions. For intermolecular friction, the heat generation rate \(Q\) within viscoelastic materials due to sinusoidal oscillating deformation can be described by the following expression, according to\[^10,19,20\]

\[
Q = \pi f \varepsilon_0^2 E''
\]

where \(f\) is the frequency of the oscillating tool, \(E''\) is the loss modulus of the material and \(\varepsilon_0\) is the strain amplitude. For ultrasonic sealing, this means that greater welding forces and bigger amplitudes lead to
more intensive heat generation. Greater welding forces additionally improve the acoustic contact between the horn and films and thus increase the effective strain $\varepsilon_0$ during the process. For greater welding forces, a significantly enhanced temperature rise in the weld zone has been detected.\textsuperscript{13}

**Process parameters and stages**

In conduction sealing, key parameters are the sealing temperature, the sealing time and the sealing pressure. Of these, the sealing temperature affects the process most. The main process parameters in ultrasonic sealing are the sealing time, the amplitude of the horn and the sealing force. In packaging processes the sealing time can normally only be varied within a small range, limited by the line speed. Typical sealing times range from a few milliseconds to several hundred milliseconds. In contrast to conduction sealing, in ultrasonic sealing, the temperature in the fusion zone cannot be set directly. The heating is influenced by the amplitude and the sealing force. The amplitude is given by the power of the generator and the transformation of the booster and the horn. Its maximum is limited by the transducer and the stability of the horn. The amplitude can be adjusted by varying the amplitude of the electrical field in the generator, typically in a range between 50% and 100%. The sealing force is normally applied by springs or fluidic actuators. Beside the afore-described influence of the welding force on the heating behaviour, the sealing force also influences the melt flow during the process. Other publications have also verified that the welding force has a significant influence on the process and resulting seam strength.\textsuperscript{14,17,19}

In the case of continuous ultrasonic sealing processes such as longitudinal seam sealing, partially gap-controlled ultrasonic sealing units were used. The gap between horn and anvil is another process parameter which must be mechanically adjusted. There is one disadvantage in gap-controlled systems: the seam quality changes because of variations in film thickness. Thus, gap control and force control also get combined in order to set a minimum gap to prevent disintegration of the packaging material and allow compensation of thickness variations by elastic elements such as springs.

Furthermore, a distinction can be made between so-called time-mode process control (where the sealing time is a fixed parameter) and energy-mode process control (where the energy value is predefined). This makes it possible to define an amount of electrical energy that will be applied by the generator during the process. If changes occur in the process conditions, for example, changes in the sealing force because of variations in the compressed air supply system, the generator automatically adapts the sealing time within a predefined range to ensure a constant seam quality.

For the intermittent ultrasonic sealing process with force control, there are four main process steps (see Figure 4). In step I, the horn attaches the films and presses them against the anvil with the predefined sealing force. In this step, the film becomes prestrained to a static horn displacement of $s_0$. In the second step (II), the vibration progresses with increasing amplitude up to its set-up value. The material starts warming up from ambient temperature $T_a$. In step III, the temperature rises to the crystalline melting point $T_m$, and the sealing material begins to flow out. Depending on the properties of the...
sealing material and the process parameters, the horn displacement reaches a stationary plateau $s_p$, which means a balanced condition between heating in the inner fusion zone and cooling at the border of the fusion zone. In this step, the melt flow decreases or even stops. By switching off the vibration, one ensures that the horn sinks into the molten material and reaches the final displacement $s_e$. The distance between $s_p$ and $s_e$ corresponds approximately to the amplitude of the horn. After the effective sealing time, the seam cools down in the last step (IV). On reaching the recrystallisation point $\delta_r$ of the material, the seam becomes almost completely resilient. This typically occurs within several milliseconds. Hence, if the application, that is the machine speed, allows an adequate cooling time, problems with open seams after sealing because of the product load may no longer arise when using the ultrasonic sealing process. In this context, the Hot-Tack property of the packaging films does not influence the seam quality as much as in conduction sealing.

The packaging market is characterised by a wide variety of different packaging materials and laminates of plastics, metals and paper. This means that the specific sealing behaviour might differ considerably from material to material. The following experimental results give an insight into the complex ultrasonic sealing behaviour of packaging films.

**EXPERIMENTS ON THE INFLUENCE OF PROCESS PARAMETERS ON SEAM STRENGTH**

**Materials and methods**

Three typical commercial packaging laminates from different suppliers (for example for packaging bakery and dairy products) were used for this study. The films consist of a biaxially oriented polyamide (PA) film having a thickness of 15\(\mu\)m as a carrier layer, and a polyethylene (PE) film having a thickness of 40\(\mu\)m as a sealing layer (see Table 1). The composition of the sealing layer differed in the three films (see Table 1).

A force-controlled ultrasonic laboratory sealing unit with a frequency of 20kHz and a laboratory conduction sealing unit were used for the tests. The ultrasonic sealing machine was additionally equipped with a triangulation laser distance sensor which allows the measurement of the horn displacement during the process. The sealing parameters for the test series are summarized in Table 2.

The seam strengths were measured with a universal tensile tester (according to DIN 55529) on samples with a width of 15mm. The sealing force is specified as ‘force per length’, so making the result independent of the sample width – the samples for sealing had a width of 100mm. A pressure value
for ultrasonic sealing with a shaped anvil cannot be calculated, unlike for conduction sealing, because of the radius-shaped anvil.

Results and discussion

In conduction sealing, the films typically behave as follows. On reaching the sealing initialisation temperature, the seam strength rapidly increases up to a maximum value (see Figure 5), which is often characterised by a plateau.\(^{18}\) The maximum seam strength reached by film 2 of about 62N/15mm is higher than that reached by film 1 (about 52N/15mm) and film 3 (about 54N/15mm). Compared with the conduction sealing behaviour, the ultrasonic sealing behaviour of the films is quite different. None of the films reached the level of seam strength reached by conduction sealing (see Figure 6). Film 1 reaches a relative seam strength of about 80% (relative seam strength=$S_{US}/S_{CS}$). The relative seam strength of the two other films is much lower (about 40%). The lower seam strength in ultrasonic sealing compared

| Description | Carrier layer | Sealing layer |
|-------------|--------------|--------------|
|             | Material     | Thickness    | Material                      | Thickness |
| Film 1      | PA 6         | 15 μm        | PE-LLD                        | 40 μm     |
| Film 2      | PA 6         | 15 μm        | Metallocene PE                 | 40 μm     |
| Film 3      | PA 6         | 15 μm        | Blend of PE-LD and PE-LLD     | 40 μm     |

PA, Polyamide; PE-LLD, polyethylene linear low density, PE, polyethylene; PE-LD, polyethylene low-density.

Table 2. Sealing parameters for the test series.

| Sealing method | Sealing force per length/sealing pressure | Sealing time | Sealing temperature | Amplitude | Tools |
|----------------|-------------------------------------------|--------------|---------------------|-----------|-------|
| Ultrasonic    | 1.5 – 7.5N/mm                            | 0.05 – 0.25s | –                   | 30μm      | Anvil with radius \(r=2.5\text{mm}\) |
| Conduction    | 2MPa                                      | 0.5s         | 100 – 160°C        | –         | Flat sealing bar with PTFE coating |

PTFE, polytetrafluoroethylene.

Figure 5. Seam strength as a function of sealing temperature for the three analysed films for conduction sealing with a sealing time of 0.5s and a sealing pressure of 2N/mm\(^2\) and using flat sealing bars.
with conduction sealing can be explained by the differences in the conditions during the two sealing processes. The mechanical treatment during ultrasonic sealing and different temperature distribution in the fusion zone (see Figure 2) causes a different and more intensive melt flow: the material flows rapidly from the inside of the seam to the outside. Resulting seam formations influence the fracture behaviour in a negative way because of unfavourable notching effects. The influence of the polymer properties on this phenomenon has already been discussed by Thürling. He assumes that this effect increases for materials with small melt ranges and a high viscosity slope with increasing temperature, which may explain the different level of relative seam strength for the three films. In all the observed films, the seam strength increases with increased sealing force up to a local maximum. At higher sealing force, the seam strength decreases again (see Figures 7 and 8). For short sealing times, the required sealing force is higher than for long sealing times. There is no typical plateau in seam strength as for conduction sealing. Despite the lower maximum seam strength for film 2 (see Figure 8), the local maximum seam strength occurs at lower sealing forces than for film 3, especially for short sealing times. In general, high relative seam strength, a widely utilisable parameter range and bonding initiation at low sealing force or sealing time are indicators for good ultrasonic sealing ability in packaging films. Film 3 also reaches a typical local maximum for the seam strength. The seam strength, however, reaches a second maximum when one increases the specific sealing force to 6N/mm (Figure 9).

Figures 10 and 11 may explain this, in which Figure 10 illustrates the movement of the horn towards the anvil, which occurs rapidly for high welding forces. Negative values at the beginning of the process, indicating a movement of the horn away from the films and the anvil, may indicate a ‘lift off’ of the horn because of the vibration. For high welding forces, the horn displacement nearly reaches the value

Figure 6. Maximum seam strength in ultrasonic sealing $S_{US}$ relative to conduction sealing $S_{CS}$.

Figure 7. Seam strength of film 1 (ultrasonic sealing) as a function of the sealing force and sealing time, for an amplitude of 30µm and an energy director with a radius of 2.5mm.
of the doubled sealing layer thickness which means nearly a complete expulsion of the sealing layer. This also is illustrated in the micrographs of microtome sections in Figure 11. This characteristic melt flow results in material accumulation at the seam sides, especially in Figures 11c and d for the higher...
sealing forces (5 and 6 N/mm, respectively). For higher sealing forces, it is also possible that the polyamide layers become partially interconnected. This may increase the seam strength. The final horn displacement $s_n$ for film 1 in Figure 12 illustrates a maximum value of less than 80 $\mu m$, which is the thickness of two sealing layers. This indicates residues of sealing material, which means that no bonding of the polyamide layers has taken place for film 1.

The horn displacement shown in Figure 10 reaches a stationary level even for high welding forces – this is the stationary plateau $s_p$ in Figure 4. This plateau $s_p$ is even reached if not all of the sealing material is pushed out, at a specific sealing force of 5 N/mm (see Figures 10 and 11c). This indicates a balanced state, and depends on the material properties and process parameters.

Furthermore, the high values of the standard deviation of the seam strength, compared with conduction sealing, are unexpected (see Figures 5 and 9). This is particularly noteworthy at high welding forces and may be associated with uncontrolled melt flow and the resulting seam formation. In general,

![Figure 11. Micrographs of microtome sections of the ultrasonically sealed seams of film 3 for different sealing forces: (a) 2 N/mm; (b) 2.75 N/mm; (c) 5 N/mm; (d) 6 N/mm.](image)

![Figure 12. Seam strength as a function of the final horn displacement for films 1 and 3 at 30 $\mu m$ amplitude and 0.2s sealing time.](image)
the high values of standard deviations may be explained by the differences in the crack and failure behaviour of the seams because of the melt formation compared with conduction sealing.

By analysing the seam strength as a function of the final horn displacement $s_e$, which characterises the seam necking due to the sealing process, it is found that the maximum seam strength occurs at specific values of about 25–30μm (see Figure 12). This means a thickness reduction of the sealing layer of about 30-38%.

**Investigation of the influence of contamination in the seam area**

The resistance to contamination in the seam area is often mentioned as being one of the biggest advantages of the ultrasonic sealing method. This is because of the expulsion of the contamination due to the vibrations. Contamination caused by the packed goods can arise during the packaging process because of incorrect filling and may result in leaking seams. The mechanisms of expulsion of the product within the seam area can be divided into (a) expulsion because of the static sealing force in combination with shaped sealing tools; (b) expulsion because of the vibration of the ultrasonic horn; and (c) expulsion because of the squeezing out of melted sealing material. This process is illustrated schematically in Figure 13.

Figure 13 additionally differentiates between contamination because of bulk materials (such as wheat flour and powders) and because of fluids and pasty goods (such as water, milk, cream and cheese). The ultrasonic sealing behaviour of contaminated seams has also been investigated by others. It was found that most of the contamination did not significantly influence the seam strength in ultrasonic sealing. Differences for different products and types of packaging films were also detected. All in all, the differences between conduction and ultrasonic sealing were found to be comparatively small.

Ultrasonic sealing mainly has advantages for loose materials such as powders, coffee and flour.

In a test series, the ultrasonic sealing behaviour of the three polyamide/polyethylene films was analysed in order to verify the results for other products. For film 3, the results were also compared with conduction sealing. The sealing bar was therefore also given a radius of 2.5mm in order to take account of the expulsion because of the tool’s shape in conduction sealing. The products were spread manually over an area of about 100 x 10mm, which is illustrated in the overhead view of the seam in the left-hand column of Figure 15. The criterion here was to achieve a uniform layer of each product. The respective amount was weighed to ensure similar conditions for each test. The amounts are listed in Table 3.

One should note that these amounts represent a worst-case scenario for completely contaminated seams. The differences in weight result from the varying deposition behaviour of the diverse products on trying to achieve a uniform product layer. The results for film 3 are presented in Figure 14. The
The standardised seam strength $S/S_0$ was calculated as the ratio of the seam strength of contaminated seams $S$ and uncontaminated seams $S_0$. The main difference between the two sealing methods is found to be for powders such as wheat flour, which produce a dramatic decrease in the standardised seam strength for conduction sealing. However, in the case of ultrasonic sealing, the standardised seam strength (about 50%) was higher than for conduction sealing (about 4%) for wheat flour contamination. In spite of the lower seam strength for ultrasonic sealing without contamination, the actual value of the seam strength of about 10N/15mm for ultrasonic sealing is even higher than the seam strength for conduction sealing (about 3N/15mm). For the salad dressing, the standardised seam strength for ultrasonic sealing is comparable with conduction sealing. However, the actual seam strength for conduction sealing (about 45N/15mm) is higher than for ultrasonic sealing (12N/15mm) because of the lower overall seam strength for ultrasonic sealing, as discussed earlier. In general, for the fluids and pasty products, the standardised seam strengths for ultrasonic sealing are lower than for conduction sealing for this film. For the fluids, this may be partly due to heat absorption by the product, which necessitates more energy input from a higher sealing force or longer sealing time for better seam strength. With solid potato chips between the films, bonding was not possible with either ultrasonic or conduction sealing. In the case of ultrasonic sealing, the chips were pulverised but not expelled. Figure 15 illustrates that the chips are embedded into the seam. Particles of the coffee powder and the wheat flour were also embedded into the seam. Those particles accumulated within the seam may function as ‘bridges’ for gas or water vapour permeability. However, physical leakage tests were not performed. In several tests with coloured solvent, however, local permeation over such ‘bridges’ has been detected for coffee powder. Furthermore, a comparison was made between the three PA/PE films used for the current tests. Figure 16 shows the differences between the films. Film 2, which is a metallocene catalysed polyethylene, gives the best results – for fluids and pasty products, the standardised seam strength is between 80% and 100%. This behaviour is also expected for conduction sealing, and it has been found that metalloocene catalysed polyethylene also behaves well for contaminated seams. For ultrasonic sealing, however, the absolute seam strength level of film 1 is greater than that of the other films. For a standardised seam strength of 63% in the case of olive oil, this means an absolute value of 25 N/15mm compared with film 2 and a standardised strength of about 86%, an absolute value of about 22N/15mm. The interesting fact in this context is that in film 1, which generally produced good ultrasonic performance without any contamination (test series on parameter influence), the sealing performance on contaminated seams is relatively low.

From these results, it can be concluded that ultrasonic vibrations of the horn mainly influence the expulsion of loose materials, by inducing a vibration of the films. This effect can be seen in the case of coffee.
powder, for example, as shown in Figure 15c. The powder which was actually located near the seam is pushed away. For fluids and pasty goods, the expulsion by the static force combined with the tool’s shape and the expulsion by the melted sealing material dominate, and this is verified by the good results for conduction sealing with profiled tools. All the presented standardised seam strength were evaluated at the same parameter setup. The sealing force for the test was the value of the highest seam strength in case of uncontaminated seams. Result of recent studies show that for higher sealing forces, the effect of expulsion of loose material and the resulting standardised seam strength even is increasing.

**ENERGY EFFICIENCY – A COMPARISON OF ULTRASONIC SEALING AND CONDUCTION SEALING**

**Materials, methods and equipment**

Ultrasonic sealing is often associated with lower energy consumption and therefore good energy efficiency. To verify this assumption, the energy consumption for conduction sealing and ultrasonic sealing was analysed experimentally. In a continuous vertical tubular bag form filling and sealing
machine, the energy consumption for conduction sealing was measured on the transversal sealing unit and compared with ultrasonic sealing; a power metre was installed to measure the effective energy consumption. Thereafter, the energy consumption for the production of one package was calculated and related to the machine speed. Two films were examined: a polyamide-polyethylene composite (15/40 μm) and a polyester-aluminium-polyethylene (PET/ALU/PE) laminate with thicknesses of 12, 7 and 80 μm for the various layers.

In talking about energy efficiency, it is necessary to define a reference parameter. For the test series, the energy consumption was compared using a parameter set-up that produces comparable seam qualities, such as seam strength and seam tightness, for both sealing methods. Hence, in preparation for the test, the optimal sealing parameters for both sealing methods were determined. In each case, two seams – the head and bottom seams – were sealed simultaneously, similar to the sealing process in form filling and sealing machines for tubular bags.

For conduction sealing, the sealing temperature and sealing time were varied in order to find an optimal setting. The maximum seam strength of the PA/PE film was achieved over a wide parameter range. For the tests, a sealing temperature of 180°C and a sealing time of 200 ms were chosen. This parameter set-up gives low energy consumption coupled with good seam properties over a wide range of machine output. For the PET/ALU/PE laminate, the maximum seam strength can only be achieved at a maximum sealing temperature of 220°C with a sealing time of more than 300 ms. For this sealing time, only a maximum output of 120 bags per minute was possible for this film. For the evaluation of optimal parameters for ultrasonic sealing, the amplitude was fixed at 40 μm and the sealing time at 200 ms, which enabled a high machine output. Both films reached their maximum seam strength for a sealing force in the range of 1000–1200 N. In Figure 17, the results for both films show a typical behaviour for the dependency of the seam strength on sealing force, as already discussed earlier. The actual seam strength is comparable with conductive sealed seams for the PET/ALU/PE film.

The PA/PE film in the indicated parameter range reaches only about 75% of the seam strength for conduction sealing. For the tests, a sealing force value of 1000 N was preferred in order to achieve a minimum energy consumption, which rises with increasing sealing force (see Figure 18). The seams with the best strength properties in the two sealing methods were also tested for leakage in a water quench. All the bags were found to be tight.

**Results and discussion**

The results of the test series in Figure 19 highlight that in the case of both films the energy consumption for ultrasonic sealing is low. Interesting is the fact that the energy consumption for ultrasonic sealing is almost independent of the machine speed. In ultrasonic sealing, energy is consumed only
during the sealing process itself, except for some joules for continuous operation of the generator. In conduction sealing, the bars have to be heated all the time. They permanently emit energy via convection and radiation, even when nothing is being sealed or the machine stops. The energy consumption for conduction sealing strongly depends on the machine speed and is reduced at increased machine output. The ratio of the sealing time on the whole time of cycle increases and hence, the relative losses because of convection and radiation decrease with increasing machine output. For the PA/PE film in Figure 19, the energy consumption even reaches the same level for both sealing methods at high machine output.

These results qualitatively agree with the investigations of Ernst⁵ who also compared the energy consumption for ultrasonic and conduction sealing. In their tests, however, the difference between ultrasonic and conduction sealing was not as great as indicated in Figure 20 for the PET/ALU/PE laminate. For this film, the energy consumption for ultrasonic sealing is only 30–40% of that for conduction sealing.

By using aluminium as a barrier layer, one can conduct the heat during sealing in lateral directions and so the heat required for bonding is deflected. This effect is amplified in conduction sealing, because the heat is transferred from the outside to the inner side of the layers. The heat has to pass
through the aluminium layer, where most of it is deflected laterally. In the case of ultrasonic sealing, the heat is dissipated within the sealing layers (see Figure 3), where the heat is needed for melting and bonding. For the thick aluminium laminate and ultrasonic sealing, even higher output rates can be achieved. The fact that the aluminium laminate has lower energy consumption than the PA/PE film is because of the more effective energy dissipation within the thick sealing layer.

This hence indicates that the use of ultrasonic sealing may help to reduce energy consumption in sealing processes. By using ultrasonic sealing energy saving especially may be possible for thick packaging materials and low machine output.

**SUMMARY AND CONCLUSIONS**

The ultrasonic sealing method has several advantages over conduction sealing, such as short sealing times for thick packaging material, less exposure of the packaged goods to heat and the ability to cool the seams under pressure. In some cases, even less energy consumption is required.

This study also shows, however, that the ultrasonic method is not the best choice for every application. For example, the test results highlight that some contaminants have a considerable effect on ultrasonic sealing. In contrast, closed and tight seams can also be produced using conduction sealing. For some laminated films, it is quite difficult for ultrasonic sealing to produce comparable seam strengths.

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Figure 19. Energy consumption for conductive sealing and ultrasonic sealing as a function of machine output for a polyamide/polyethylene laminate.

Figure 20. Energy consumption for conduction sealing and ultrasonic sealing as a function of machine output for a PET/ALU/PE laminate (layer thicknesses: 12/7/80μm).
to conduction sealing. The quality of the sealed seams depends significantly on the properties of the sealing materials. This aspect is the subject of ongoing research.

In conclusion, it can be stated that ultrasonic sealing is an interesting alternative to conduction sealing, but it has yet to be confirmed that all the theoretical advantages transfer to the packaging process. Higher investment cost and often higher complexity of process integration have to be weighed up against the benefits.

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