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TECHNOLOGY AND INNOVATION IN FOOD PACKAGING

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ABSTRACT

In this work an in-depth analysis of the food packaging industry is presented. The target is to provide the reader with an overview on food packaging, especially on primary packaging, with regard to the machines present in this sector, their characteristics and critical issues. Subsequently two fundamental aspects, which can be found in all primary food packaging machines, are analyzed in detail.

At first, motor-reducer couplings are analyzed, for which an innovative sizing method, particularly suitable for packaging machines, is presented, together with some improvements in order to take into account both the non-constancy of the reducers efficiency as the operating conditions change and the fatigue life of the bearings in the gearboxes. Then a focus on conduction and ultrasonic welding techniques is presented, making a comparison on the basis of the results of some experimental tests.

AKNOWLEDGEMENTS

A special thanks to Prof. Roberto Caracciolo for the support in this thesis work.
A big thank you also to all the friends who have always been with me.
Finally, thanks to all my family, without whom I certainly would not have been able to achieve this goal.
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CONTENTS

INTRODUCTION

Nowadays, in the industrial world, packaging represents a sector of great importance; in particular, the packaging sector is often linked to food. Moreover, the continuous growth of the world population and the increasing need for portioned and practical to manage foods make food packaging, and in particular primary food packaging (i.e. everything related to the creation of the protective wrapping directly in contact with the product), a rapidly expanding sector.

The machines for primary food packaging can be divided into three types, horizontal, vertical and stand-up pouch, depending both on the direction of advancement of the film and the direction of loading of the product inside the bags; all these machines generally make it possible to form bags, fill them with the product and finally close them. Furthermore, it is possible to say that the "heart" of these machines is the system for the realization of transversal welds; three solutions are distinguished: rotary, Long Dwell and Box Motion.

Another aspect to consider is the type of film that is used to create the bags as upon this depends, for instance, the chance of achieving high productivity while still ensuring hermetic welds.

In modern machines, electric axes are often used in order to increase flexibility in production, that is the differences in the dimensions of feasible packages, and this leads to many motor-reducer couples (up to 12 on a horizontal machine and 20 or more on a stand-up pouch machine): this leads to the need for a sizing method of these units that allows to maximize both flexibility and production volumes of the machine.

In the following of this work two of the most utilized welding technologies in food packaging are presented, conduction and ultrasonic welding.

The discussion concludes with the analysis of the results of some experimental tests carried out in order to compare the performance of the two welding technologies, specifically in terms of sealing strength of the welds, efficiency and, with regard to the ultrasonic welding, the effects of the presence of product on film edges before welding, a situation that can occur in food packaging systems and for which ultrasonic welding represents a valid solution.

Finally, a brief analysis of future developments in the world of food packaging is presented.

CHAPTER 1

STATE OF THE ART IN FOOD PACKAGING

The aim of this chapter is to give a description of the most important aspects in the food packaging sector, focusing in particular on primary food packaging. In the first paragraph an introduction to food packaging is made, in the second paragraph the most important machines are analyzed, in the third paragraph an analysis of the main materials used in food packaging films is presented and finally in the last paragraph some considerations are proposed relating to flexibility, a fundamental aspect in current food packaging plants.

1.1 Introduction to food packaging

In today's society, packaging surrounds, enhances and protects the goods we buy, from processing and manufacturing, through handling and storage, to the final consumer. Without packaging, materials handling would be a messy, inefficient and costly exercise and modern consumer marketing would be virtually impossible.

A distinction is usually made between the various "levels" of packaging.

A *primary* package is one that is in direct contact with the contained product. It provides the initial, and usually the major, protective barrier. Examples of primary packages include metal cans, paperboard cartons, glass bottles and plastic pouches. It is frequently only the primary package that the consumer purchases at retail outlets.

A *secondary* package, a corrugated case or box for instance, contains a number of primary packages. It is the physical distribution carrier and is increasingly designed so that it can be used in retail outlets for the display of primary packages, in which case it is referred to as "shelf ready".

A *tertiary* package is made up of a number of secondary packages, with the most common example being a stretch-wrapped pallet of corrugated cases.

Three primary functions of packaging may be identified: *containment, protection* and *communication.* These three functions are interconnected and all must be assessed and considered simultaneously in the package development process.

Containment: all food products must be contained before they can be moved from one place to another. The "package", whether it is a bottle of cola or a bag for a snack-bar, must contain the product to function successfully.

Protection: this is often regarded as the primary function of the package: to protect its contents from outside environmental influences such as water, water vapor, gases, odors, microorganisms, dust, shocks, vibrations and compressive forces.

For the majority of foods, the protection afforded by the package is an essential part of the preservation process: in general, once the integrity of the package is breached, the product is no longer preserved.

Communication: the ability of consumers to instantly recognize products through distinctive shapes, branding and labeling is directly related to the package in which products are contained. Other communication functions of the package are equally important: today, the widespread use of modern scanning equipment at retail checkouts relies on all packages displaying a universal product code (UPC) that can be read accurately and rapidly. Furthermore, nutritional information on the outside of food packages has become mandatory in many countries.

At last it is important to note that there are several drivers for packaging innovations. One is the fast-changing social trends and the increasing consumer demand for convenience and safety. Another is growing environmental awareness, while profitability and differentiation are also important for food companies seeking to attract consumer attention. Sustainability will receive increasing attention and a plethora of labels such as carbon footprint and paper from sustainably managed forests will indicate how companies are performing in this area. Because consumers want innovation and value novelty, the packaging industry must continue to innovate or risk stagnation.

1.2 Classification of primary food packaging machines

The machines for primary food packaging can be divided into three types depending both on the direction of advancement of the film and the direction of loading of the product inside the bags; all these machines generally make it possible to form bags, fill them with the product and finally close them, in particular the three types are as follows:
- *horizontal flowpack machines*, in which the film advances horizontally and also the product is loaded horizontally;
- *vertical flowpack machines*, in which the film advances vertically and also the product is loaded vertically;
- *stand-up pouch machines*, in which the film advances horizontally while the product is loaded vertically.

1.2.1 *Horizontal flowpack machines*

The horizontal form-fill-seal (HFFS) is characterized by machines (Fig. 1) where the film, which is held by the reel, is laid down, via mobile guides, on the *folding box*, i.e. a forming tube which, thanks to its particular design, favors the modeling of the film into a tubular shape (Fig. 2):

Figure 1: Example of horizontal flowpack machine [1].

the tubular, which forms continuously on the machine (because a typical characteristic of horizontal machines is that the film is unroll at constant speed), is often referred to as a *flow pack*.

Figure 2: Example of a folding box in an horizontal wrapping machine [2].

The tubular is sealed longitudinally by means of special heat-sealing systems that work continuously, such as welding wheels (Fig. 3) or band welding (par. 3.2). The longitudinal welding can be made, depending on the different configurations of the machines, on the upper or lower side of the machine itself; in any case it results substantially contemporary to the filling with the product.

Figure 3: Example of a welding wheels unit in an horizontal wrapping machine [3].

The cycle is completed with the transversal welds: these occur in a single operation since the system usually forms and divides with a cut in the middle both the second and the first cross welding of two successive packages in a single phase (Fig. 4).

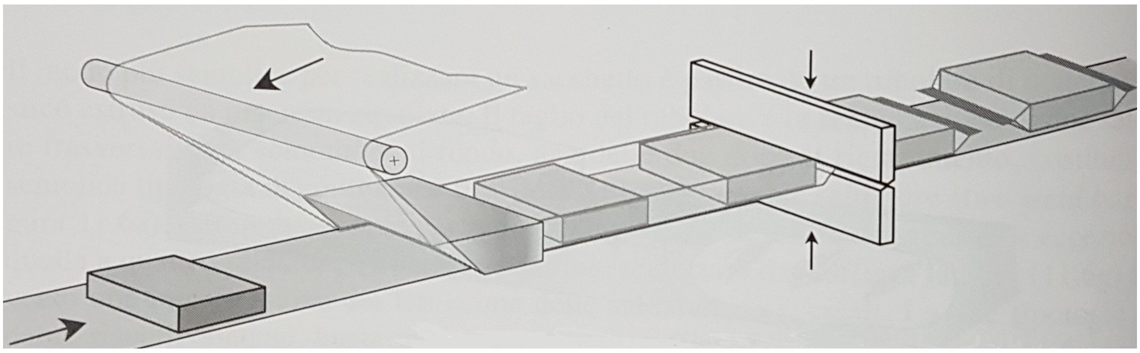

Figure 4: Schematic view of the cross welding in an horizontal wrapping machine [18].

Various solutions are also available for transversal welding, both from the mechanical point of view (rotary systems, long dwell or box motion, see paragraph 1.2.4), and from the welding technology point of view (Chapter 3), depending on the material used, the speed request and the specific product to be packaged. For ice cream and chocolate coated products, as an example, cold welding systems can be used in order to prevent heat from damaging the products, so both longitudinal and transverse welding systems are used based almost exclusively on pressure applied on the edges of the material to be joined. Alternatively, most frequently used technologies are conduction and ultrasonic sealing, the latter being a very recent technology (paragraph 3.3) which does not require preheating time and therefore allows the machine to be immediately ready, and it is also an efficient system on many different materials.

In Fig. 5 an example image of a wrapping machine is shown: products are usually transported into the machine via a belt conveyor or a lug chain, the film feed roller can be positioned higher ("BA" version, film from above) or lower ("BB" version, film from below) with respect to the plane of the products (depending on the specific application), the unrolled film passes, together with the product, into the forming box that folds it around the product itself; at this point, the bottom part (in case of BA version) or the upper part (in case of BB version) of wrapped product goes in between some couples of rollers which pull and longitudinally seal the film, finally the end sealer mechanism makes the cross seals and at the same time splits individual packages which leave the primary packaging machine on the discharge conveyor.

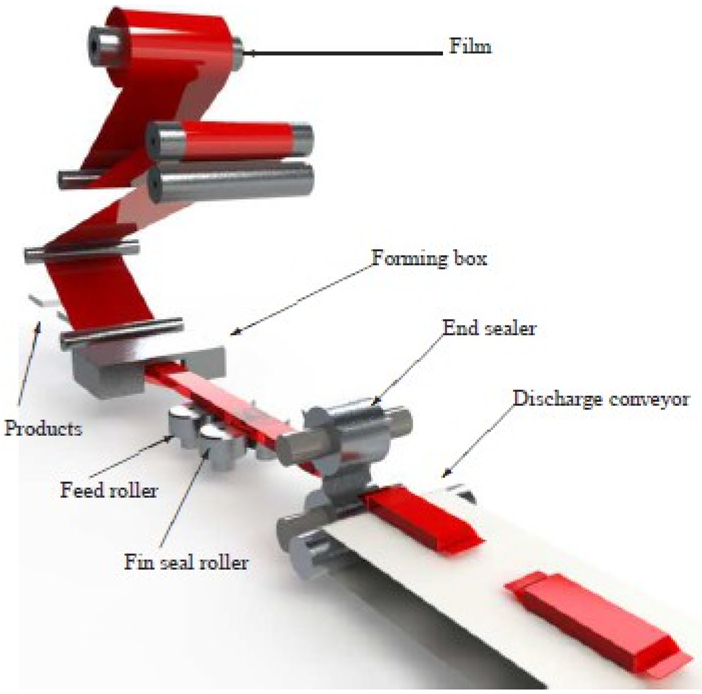

Figure 5: Schematic view of an horizontal wrapping machine [12].

About the positioning of the film, as mentioned above, the horizontal flowpacks are divided into two versions: BB to BA.

The BB version (Fig. 6) is characterized by the film reels placed under the product sliding surface: in this case the product is placed on the film which is then rolled around it and so the longitudinal welding is performed on the top part of the package; with this solution it is the film itself that, advancing, carries on the product inside it. The BB version is generally used when there are not high speeds and fragile products.

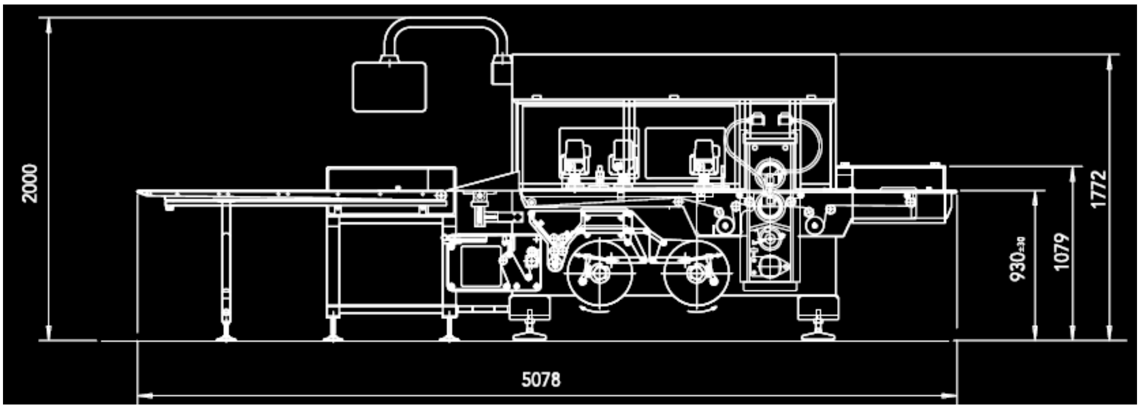

Figure 6: Schematic view of an horizontal wrapping machine, BB version [4].

The BA version (Fig. 7) is characterized by the film reels placed above the product sliding surface: in this case the product is carried forward, up to the longitudinal sealing station, from the pin chain, the film wraps the produced from above and the longitudinal welding is then performed on the bottom of the package. The BA version is generally the most used because it allows to reach higher speeds than the BB version.

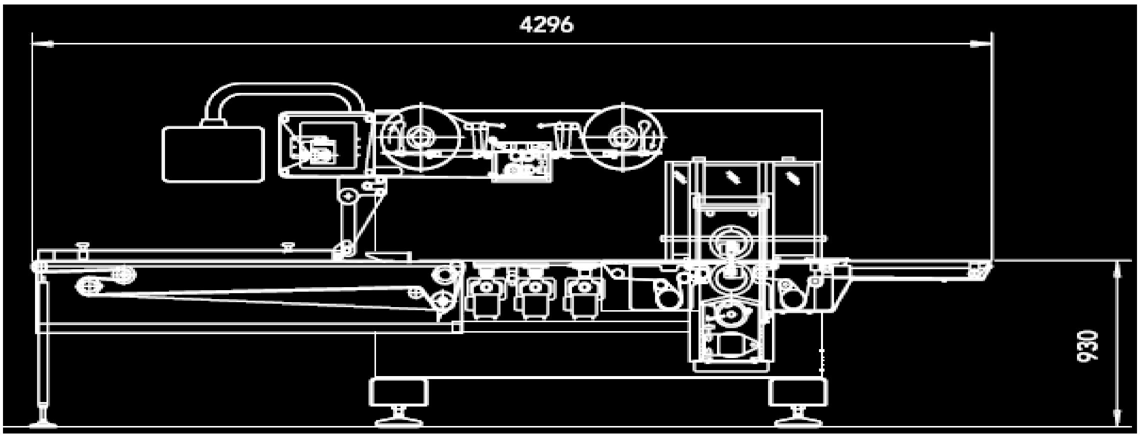

Figure 7: Schematic view of an horizontal wrapping machine, BA version [4].

Another element of distinction between the different horizontal flowpacks is the transversal welding system: as detailed in paragraph 1.2.4, there are three possible versions, rotary, Long Dwell or Box Motion. Various factors depend upon the chosen welding system, among them the maximum height of the products that can be packaged (in the case of high products, the rotary system is generally not suitable, Long Dwell or Box Motion must be provided) and the maximum feasible speed (rotary welding systems are the most performing in this regard). Moreover, for what concerns the transversal welding with Long Dwell or Box Motion systems, in some machines special sensors are provided in order to measure the dimensions of the incoming product and then correctly synchronize the electric axis of the welding system in order not to risk crushing the product between the welding jaws, a very useful option in case of natural products, not always the same in size, or to facilitate format changeover.

Finally, an additional option that not all flowpack machines present is the possibility of packaging products in modified atmosphere (MAP). The system consists (Fig. 8 - 9) of a tube that blows the gas inside the tubular film (*gas flushing*) and is removed only immediately before the last cross seal that closes the package; in this way, within the package there will be a specific gas, normally used in order to increase the shelf life of the product, i.e. the time that this product can withstand, in closed package, without deteriorating.

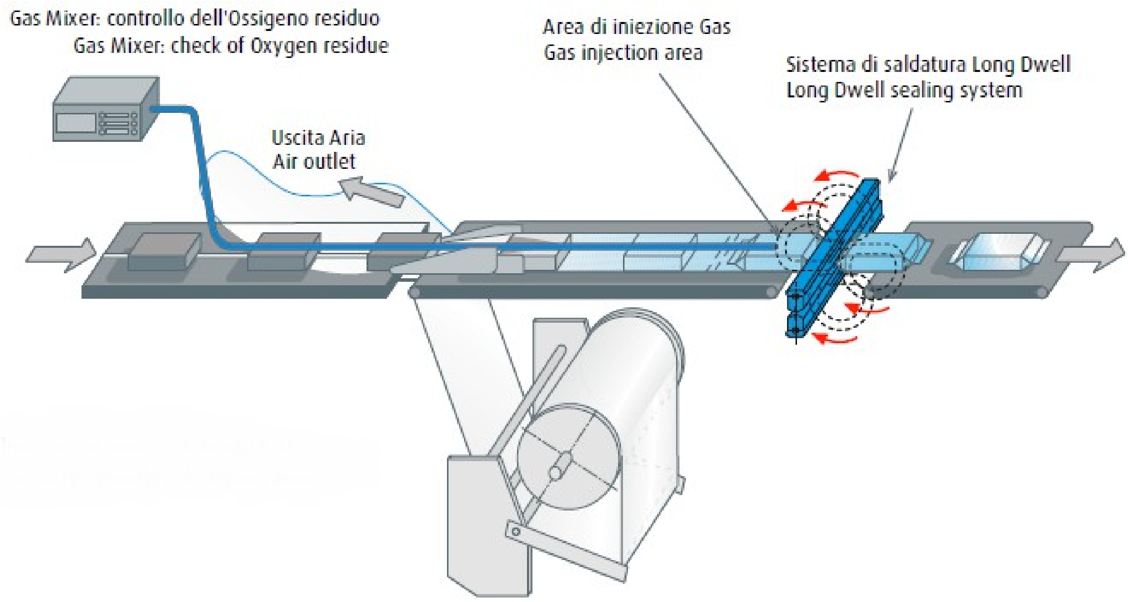

Figure 8: Productive cycle with modified atmosphere (MAP) [3].

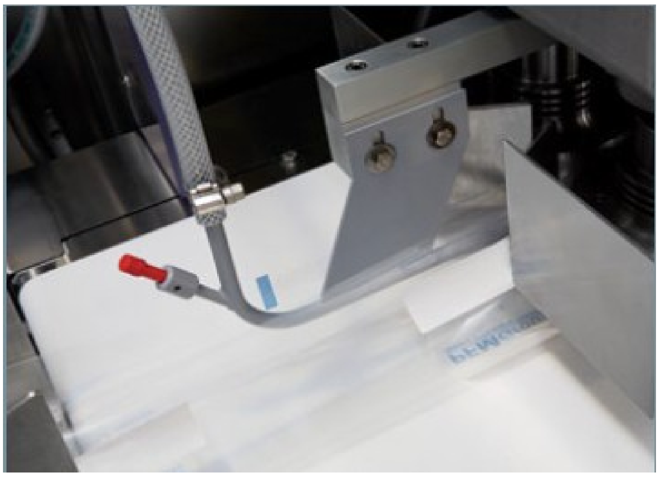

Figure 9: Gas injection area with modified atmosphere (MAP) [3].

As for the dimensions of packageable products and achievable speeds, these factors vary from machine to machine, thus introducing an additional element of differentiation between the models. In particular, good horizontal flowpacks can reach, with products length between 60 and 350 mm, width between 10 and 200 mm and maximum height of 100 mm, a productivity of 200 cycles/min with a single bar Long Dwell welding system, which increase up to 400 cycles/min with double sealing bar. With rotary welding systems and particularly compact products (e.g. chewing-gum) feasible productivity can be around 1500 cycles/min, considering to use high-speed cold-sealable films. Lastly, for natural green products (Fig. 10), even of large dimensions, having an automatically adjusted length, width between 10 and 380 mm and maximum height of 230 mm, Box Motion type welding systems are used and maximum productivity of 40 cycles/min is achieved.

Figure 10: Examples of green packageable products.

1.2.2 *Automatic loading in horizontal machines*

In horizontal flowpack machines, the loading of the product is an operation that can be performed manually, that is by operators whom place the products on the appropriate lug chain or on the belt conveyor, or automatically, especially when productivity increases (an example are bakery products, which come out massively from tunnel-type ovens or cooling tunnels and must be placed in the packaging machines in an orderly manner).

Regarding the automatic distribution and loading systems there are several options, as exposed in the following.

Blades for alignment by rows: when products exit the oven or cooling tunnel, they are never perfectly aligned; therefore, there exist specially designed blades to ensure that the products, by leaning on them, are aligned by rows and then the blades "run away" and reappear again at the same point to align the next row of products.

Pivot distribution station: it distributes the rows of products towards the flowpack wrapping machines (Fig. 11). This system operates electronically by means of motors in electric-axis and is designed for the handling of delicate products, including those of irregular shape.

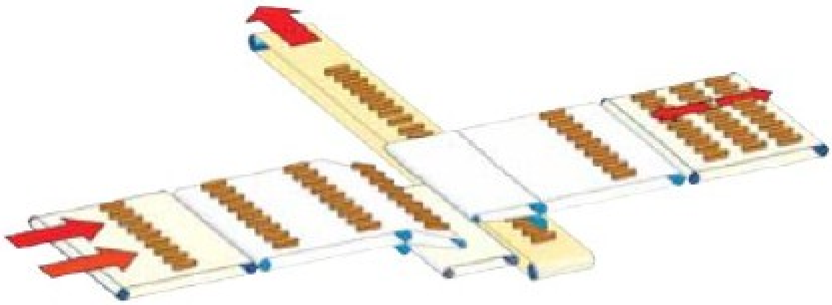

Figure 11: Schematic view of a pivot distribution station [5].

90° - 110° cross feeder: this is a flexible system (Fig. 12 – 13) incorporating two or more synchronization belts, driven by servo-motors, which follows the speed of the production flow.

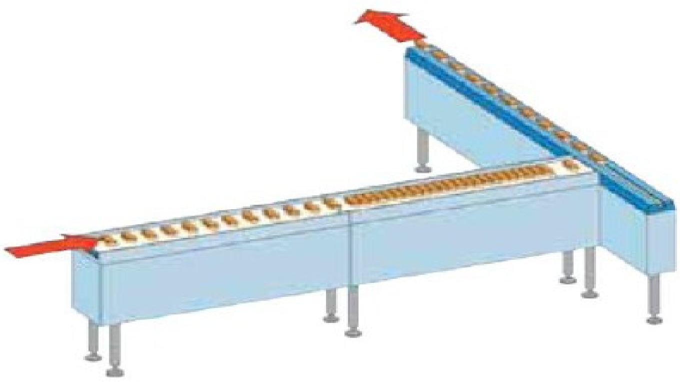

Figure 12: Schematic view of a 90° cross feeder [5].

Figure 13: Image of a 110° cross feeder [5].

Automatic in-line feeder: this is an high-speed, in-line feeding system (Fig. 14). It is ideal for both regular and irregularly-shaped products. Suitable for products that cannot sustain accumulation pressure or contact. This system can have up to five synchronization belts driven by servo motors in electric-axis; furthermore the belt speed is calculated automatically, according to product flow.

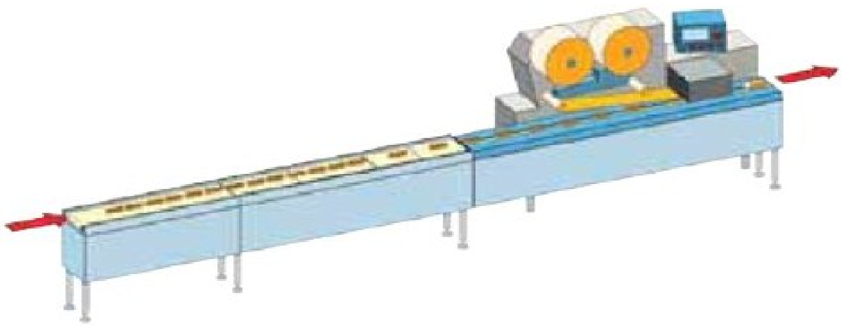

Figure 14: Schematic view of an automatic in-line feeder [5].

Grouping system: this is an high-speed, in-line feeding system for multipacks (Fig. 15). The number of products in the multipacks can be easily programmed and the synchronization with the wrapper is extremely accurate.

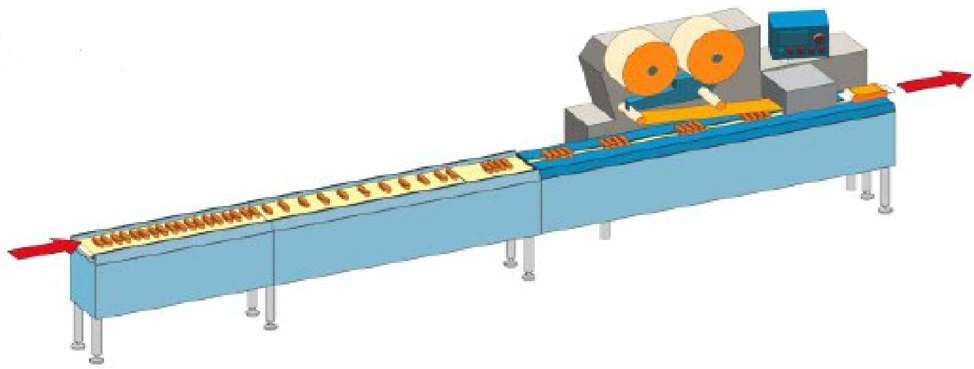

Figure 15: Schematic view of a grouping system in-line feeder [5].

It is important to note that in these two feeding systems (*Automatic in-line feeder* and *Grouping system*) the idea is to create the correct spacing between the individual products (or between groups of products) in order to correctly feed the following horizontal flowpacks. In order to do this speed differences between subsequent

conveyor belts, calculated using appropriate algorithms, are exploited. In general two strategies may be distinguished: the first consists in starting from a generic no contact (situation in which the individual products are not in contact with each other), a soft contact is created (situation in which the products are in light contact with each other) and then the no contact is created again with the correct spacing; the second consists in keeping all the products in storage and then passing them one at a time onto a conveyor belt with a higher speed, again, in order to space the individual products with each other.
Orienting system: it turns the arriving products of 90° to present them to the feeding system with the short side leading. Available for regular or irregularly-shaped products (Fig. 16).

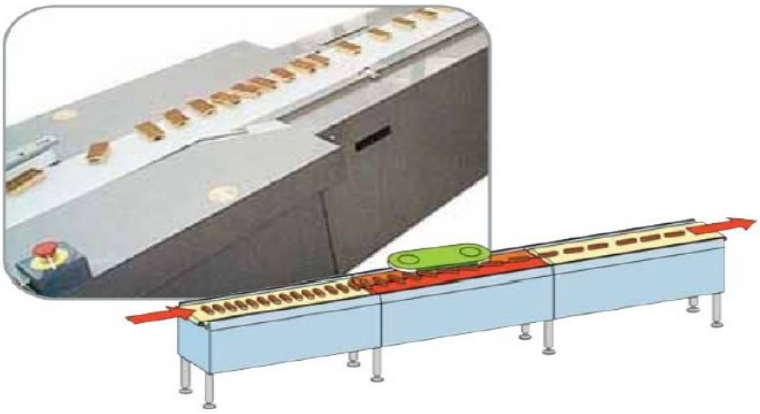

Figure 16: Schematic view of an orienting system in-line feeder [5].

Another way to feed horizontal flowpacks is to utilize robotic automation (Fig. 17). In this way it is possible to exploit aspects such as the vision system or vacuum end effectors. In particular, when vision is incorporated with feed placing, product can be presented in random orientation and still be picked and placed in the correct orientation into a wrapper infeed belt conveyor or lug chain. The ability of the delta robot to track both the incoming product flow and target conveyor, allows the robot to seamlessly pick and place product without disrupting the flow of the packaging line.
Furthermore the picking device at the end of the robot arm, known as the end-effector, is available in numerous configurations to pick-and-place nearly any item (Fig. 18).

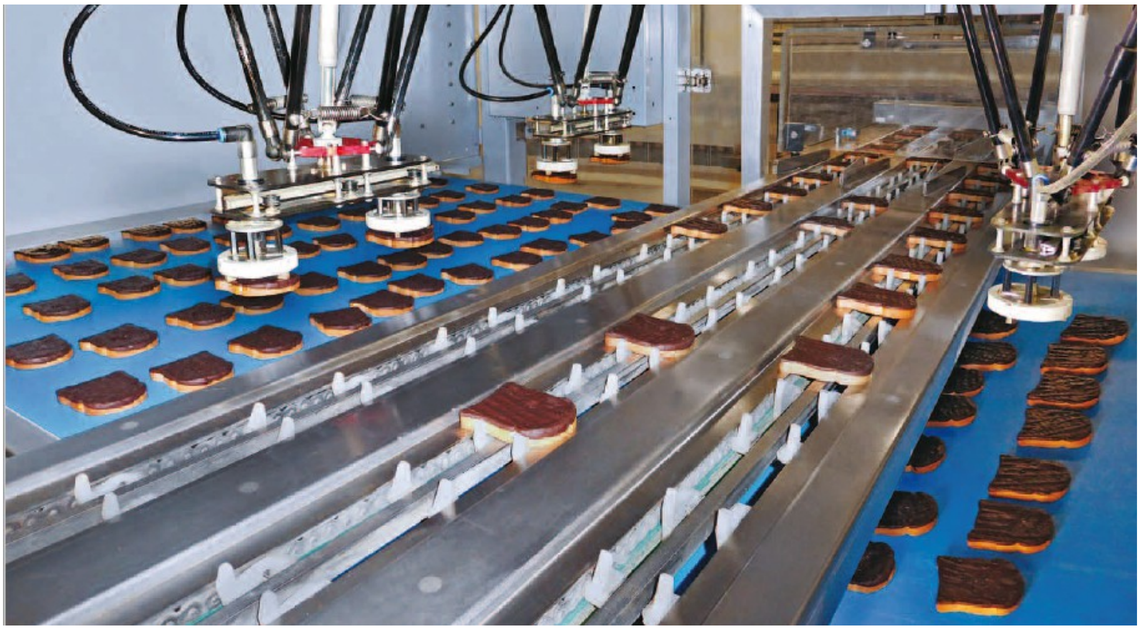

Figure 17: Example of Delta robots feeding some horizontal wrapping machines [6].

Most common are the vacuum suction cup style (feed placing with vacuum allows for delicate handling of product preventing damage to the product itself) and mechanical grippers. End-effectors are available as a single pick or multiple pick option. The multi-pick option can pick from two to twelve items at once. Also available is reflex pick technology, which allows you to pick an individual product, retract, and then pick another product with the same end effector using a different vacuum system. Each product picked can then be individually oriented to the other products, using a 4th axis of motion to rotate the product, to create the ideal pack pattern.

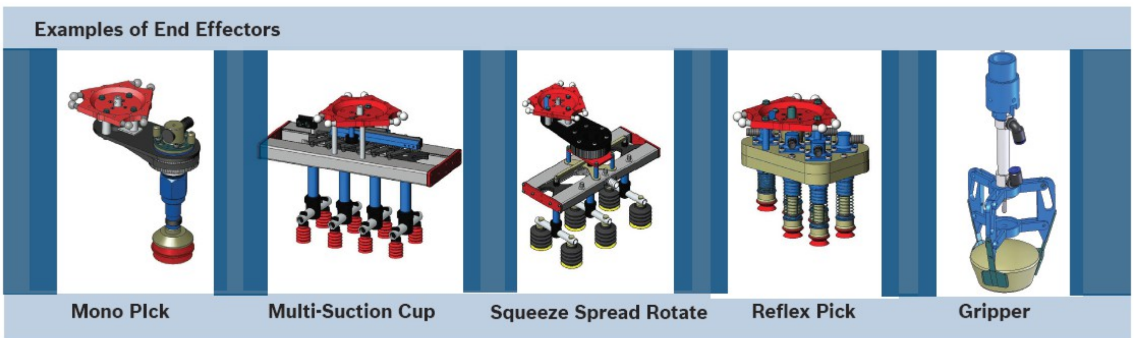

Figure 18: Examples of end effectors [6].

Feeding placing can be handled in one of three pick & place patterns: *collation*, *cross belt* and *inline or parallel*.

Collation (Fig. 19) is probably the most common of the three types. This means incoming product is presented in a single stream to the collator chain where it is collated in groups, picked with a defined product count and placed in a lug chain of an horizontal wrapper. Often multiple products are picked together using "squeeze and spread" end-effector technology. This dramatically increases the throughput of the robot by picking multiple products with each pick. A key benefit in using *collation* is that vision is not required because product is already oriented in the collator chain.

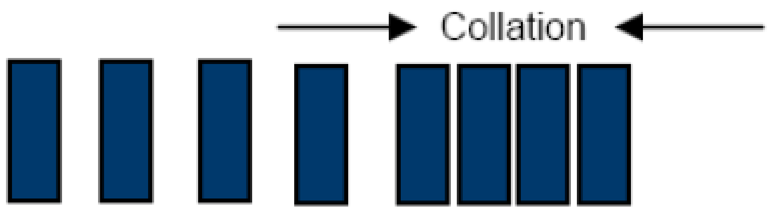

Figure 19: Collation [6].

The second type, *Cross Belt* (Fig. 20), indicates incoming product flow is perpendicular to the out-going flow. *Cross Belt* is ideal for products coming in at a random placement and orientation. This is typically used in feed placing for the primary packaging of raw product. For instance, picking product from a belt directly after an oven or bar extruder and placing it into the lug chain of a wrapper, is a common cross belt application. Vision is often required in these applications since the products are usually not oriented prior to entering the robotic cell.

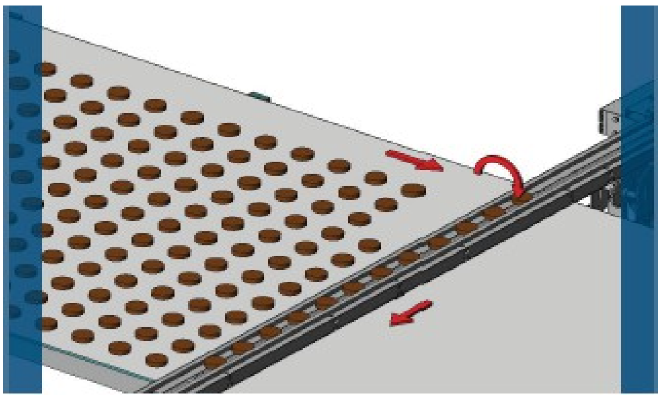

Figure 20: Cross Belt [6].

The third type, *Inline or Parallel* (Fig. 21), allows incoming product to flow parallel to the out-going flow. Inline is commonly used when the product is arriving in single or multiple streams, or on a narrow belt. Counterflow is often the most efficient way of presenting the product with respect to the progression of the lug chain in the robot cell, meaning the two flows oppose each other as they enter the robot cell. This ensures that the robot arm responsible for making sure a slot in the lug chain is full before leaving the robot cell has a full stream of product to quickly pick from.

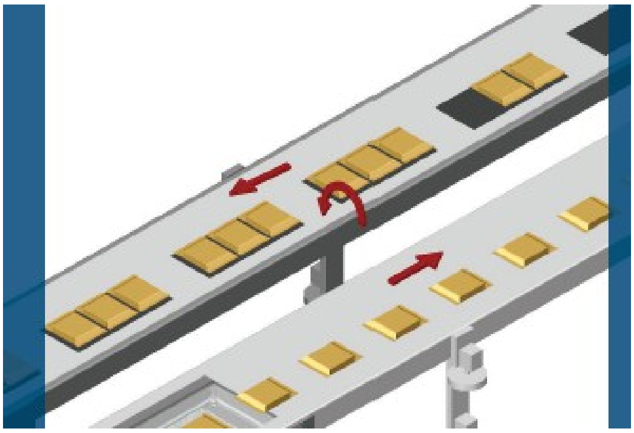

Figure 21: Inline or Parallel [6].

1.2.3 *Vertical flowpack machines*

Vertical machines are generally intended for free flowing products, i.e. granular, powder, in small pieces or liquid products. These products are packaged in a process schematically illustrated in Fig. 22. As shown in the figure, a flat film (1) of packaging material wound around a reel (2) is drawn at high speed and delivered to the *forming collar* (3) (a triangular conveyor whose design and dimensions are fundamental for the success of the operation) which smoothly forms it into a cylinder (4) to be filled with a product. The film-forming process should also bring the outer edges of the film together and overlap them to create a seam (5) along which the film will be sealed. The target product (6) is then dropped into the sealed film which is then cross-sealed (7) and cut to form the complete pouch (8). The cross seal is also the bottom seal for the next pouch.

Most commonly the cylinder (4) is of circular cross-section. Figure 23 show cross-sections of the film formed inside the cylinder for typical seam shapes.

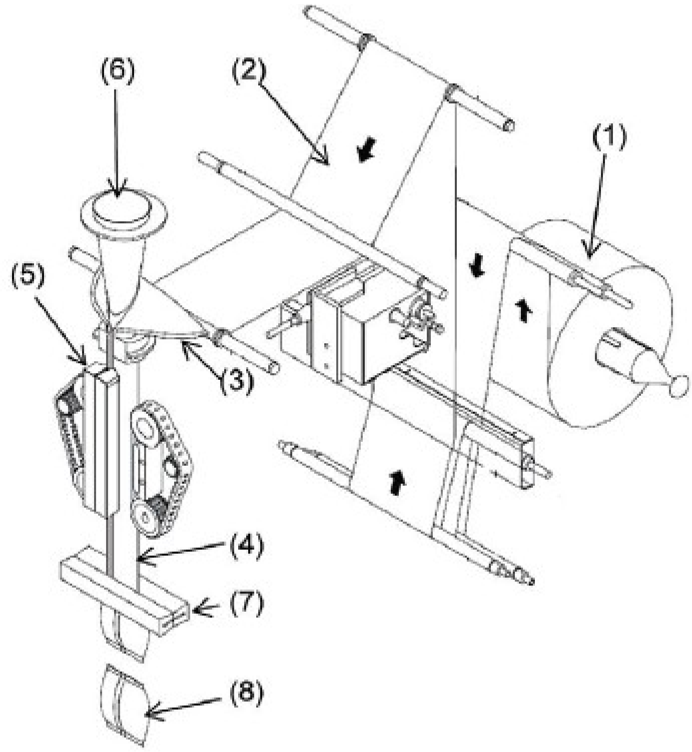

Figure 22: Schematic diagram of a vertical form-fill-seal machine.

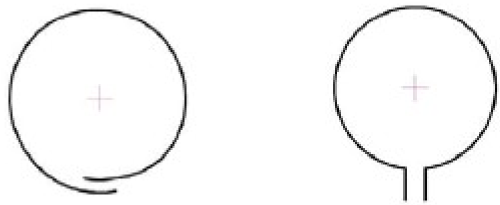

Figure 23: Film cross-section inside the cylinder in the case of a lap seam (left image) and in the case of a fin seam (right image).

Compared to horizontal flowpacks, vertical FFS (VFFS, vertical form fill seal) may be slower both because the product, advancing from top to bottom by falling, tends to form the so-called "queue", and therefore it is important to wait until the end of this queue of product in order to be able to close each bag, and because the cross welding is immediately subjected to tension due to the weight of the product contained in the flowpack; therefore, the transverse welding phase must last for the time necessary for the sealing to cool down and become tenacious (see Hot Tack problem, Chapter 3). Furthermore VFFS machines can be intermittent or continuous unlike horizontal machines which are always continuous.

In general there are two ways to implement the intermittent transverse welding cycle: it is possible either to drop the product directly into the newly welded hanging bag (feasible for light products) or to weld the bag base, slightly open the welding jaws in order to not burn the film and, keeping the jaws semi-closed, load the product in the hanging bag; in this way part of the weight is supported by the jaws and does not suddenly fall on the welding of the bag.

Another problem that characterizes vertical wrapping machines is the possibility that the inside of the film gets dirty during the fall of the product; if this happens in the area where the film has to be welded it can compromise the quality of the sealing: this problem is more likely to happen with dusty products such as chips, popcorn etc. but in general it could occur with all products if a part of the product itself, during the fall, due to the impacts with other parts of the product, follows a trajectory longer than expected (helical adjacent to the walls of the film for instance) and therefore is still in between the welding jaws when they close.

To solve the problem, a "stager" is used: it consists of a system, placed above the welding jaws, which closes, compressing the film, before the sealing bars, stopping the "delayed" product crumbs on itself; then, once closed, it is necessary to wait a certain amount of time to be sure that the crumbs just after the stager have entered the bag and then it is possible to close the jaws, after the welding then the machine reopen both the jaws and the stager and advances the film loading new product to form the next bag. This solution, however, is good for intermittent vertical machines, but these, due to the limits on the intermittent drive of the film (high accelerations, slipping of the film on the rollers, etc.), can reach a maximum of 140 bags/min.

Regarding vertical continuous machines, these are normally realized with rotary or Box Motion welding systems but between these two the rotary one allows to reach much higher speeds (because Box Motion, in vertical configuration, has inertial problems): the issue of the continuous vertical machine with rotary cross welding system consists in developing a proper stager. A solution to this problem was found by TNA Solutions

Ltd. with ROBAG 3 (Fig. 24): this machine reaches up to 250 packages/min with a rotary welding system with three sealing bars.

Figure 24: ROBAG 3 [7].

For what concerns the drawing of the film wrapped around the tube, on vertical machines there are normally two solutions. The first is to use high friction straps which push the film against the tube which in turn will be coated with a low-friction material (Teflon, for instance). A better solution is to use vacuum belts (Fig. 25), which, by means of specific holes and a vacuum chamber, make the film adhere to them and then pull it downwards.

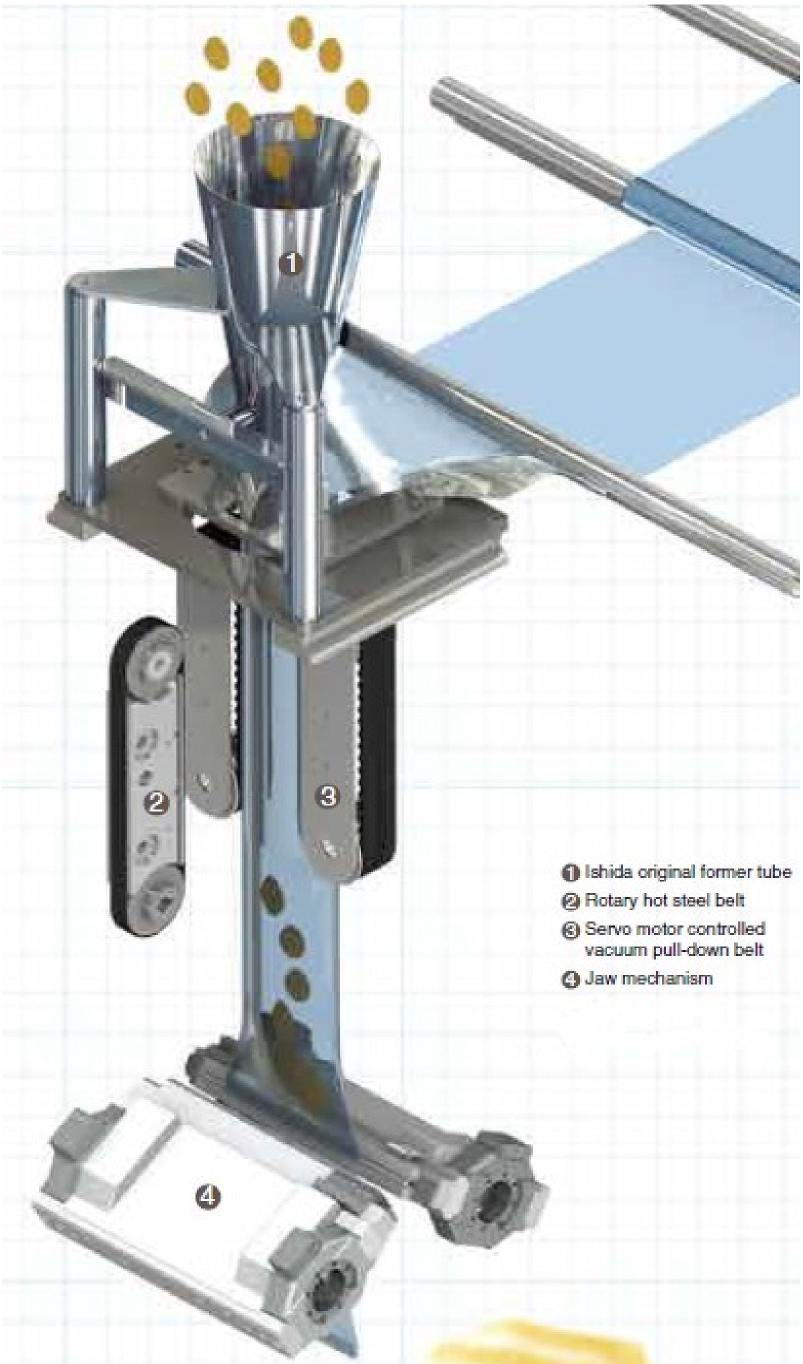

Figure 25: Schematic view of vacuum pull-down belt [8].

Finally, regarding the feeding systems for vertical machines, it is possible to distinguish four main solutions, which are shown below.

Auger dosing unit: it consists of a loading hopper, inside which a worm screw (auger) turns. A specific amount of product is dosed according to the number of revolutions and the screw pitch. This is ideal for very fine products (Fig. 26).

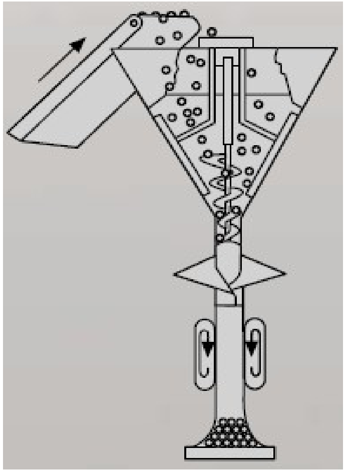

Figure 26: Auger dosing unit.

Volumetric dosing unit: it has the task of dosing a specific amount of product. It can be adjusted and is suited to granular products (Fig. 27).

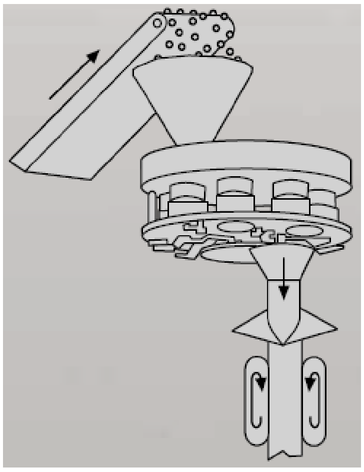

Figure 27: Volumetric dosing unit.

Linear scales with vibrating surfaces: they are used for granular products with medium to large dimensions and includes a set of vibrating surfaces, which push the product towards the weighing cell. As soon as the programmed weight has been reached, the vibrating surfaces come to an immediate halt and the weighing cell empties its contents into the wrapping material forming collar on the packaging machine (Fig. 28).

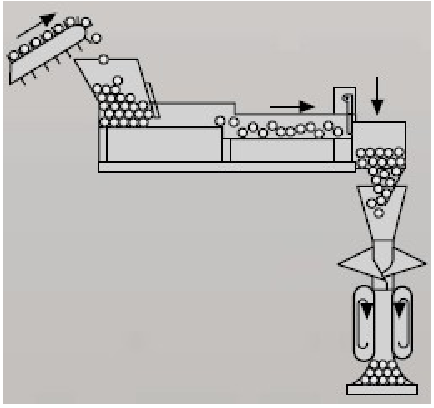

Figure 28: Linear scales with vibrating surfaces.

Multihead weigher: multiple combination weighing system: it is a fast, accurate, reliable and hygienic solution. It is available in various models to suit specific requirements. The ideal weighing solution for achieving high production levels with maximum accuracy (Fig. 29).

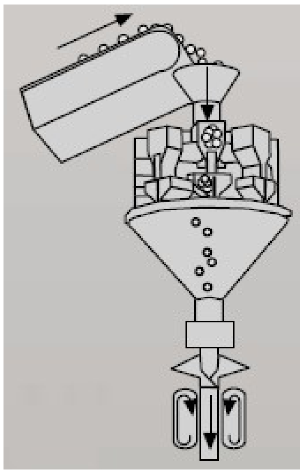

Figure 29: Multihead weigher.

1.2.4 *Welding solutions in food packaging machines*

In the food packaging industry it is possible to say that the "heart" of the flowpack machines consists in the welding system (both from the welding technology point of view, see Chapter 3, and from the of mechanical realization point of view). More specifically, the set of components that deals with the transverse welds of the packages

is of great importance: in general, regarding the mechanical aspect, three types of solutions can be distinguished: rotary, Long-Dwell and Box Motion systems.
The *rotary welding system* consists of a pair of counter-rotating rollers and one or more sealing bars which are fixed on their circumference (Fig. 30). The film containing the product passes between the two rollers which rotate according to a law of motion such as to ensure that the tangential velocity of the sealing bars is equal to the linear speed of the film when the bars of a roller meet with the respective bars of the other roller in order to weld the two edges of the film and then seal the package.

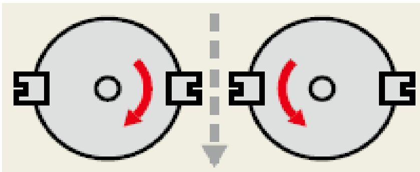

Figure 30: Schematic view of a rotary welding system with two sealing jaws for each roller [8].

This system consists of a single electric axis and is usually used for high speeds or economic machines. It is also important to use high weldability films or cold welding films (i.e. films that are sealed by mechanical compression) because of the reduced welding time of the rotary system compared to other solutions.
From the design point of view, motor-reducer units are normally used: considering a productivity of 200 packs/min, it is usual to choose motors with a maximum speed of around 3000-4000 rpm combined with a reducer with a reduction ratio of about 1/10 or 1/8; for particularly high speeds it is possible to reach 1/6 reduction ratios. Some manufacturers have finally tried to use torque motors, as they have the advantage of not needing the gearbox, a component that often heats up and can be a source of inaccuracies, but this solution has had low diffusion due to high costs.
The rotary welding system is therefore utilized, for instance, on horizontal flowpack machines with 400 packages/min (like machines for snacks packaging, where thin films are used which can be welded in 10-30 ms and where a pair of welding jaws is provided on both rollers in order to increase the feasible productivity) or on economic machines

where therefore the angular speed of the rollers varies to obtain the correct welding time.

The *Long-Dwell* (or *D-motion*) *welding system* permits the welding bars to perform a "D" trajectory, where the rectilinear section is placed parallel to the direction of film advancement. This system (Fig. 31 – 32 - 33), compared with the traditional rotary system, given the same speed of the film, enables a longer sealing time because of the fact that the sealing jaws are able to “follow” the package during all the length of their rectilinear trajectory; this aspect guarantees that even thick films are tightly sealed.

Furthermore, in horizontal machines, high speed hermetic seals at up to 200 cycles/min in case of a single welding bar per each “D”, and up to 400 cycles/min in case of two welding bars per each “D” are feasible; in vertical machines, on the other hand, it is possible to achieve a maximum productivity of about 125 cycles/min in case of a single welding bar and 200 cycles/min in case of two welding bars due to other limits of the vertical configuration, as already discussed in the previous paragraph.

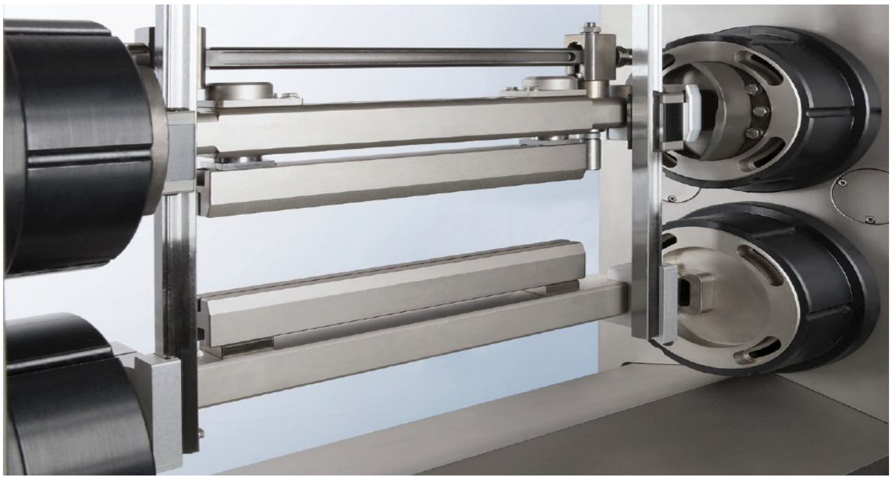

Figure 31: Long-Dwell welding system [4].

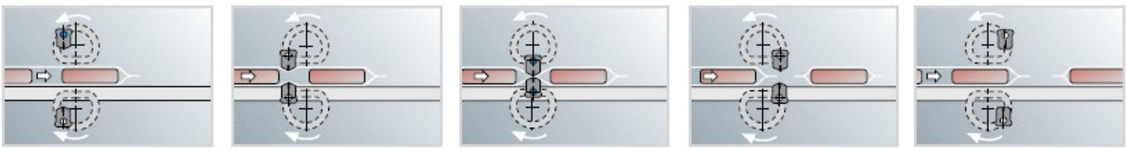

Figure 32: Long-Dwell operating phases, with one sealing jaw for each”D” [4].

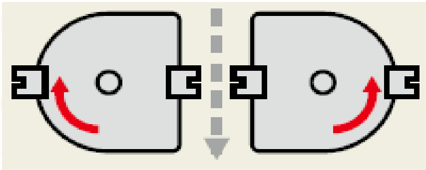

Figure 33: Long-Dwell with two sealing jaw for each"D" [8].

The *Box Motion welding system* consists of a system with two degrees of freedom, one for moving along the direction of film advancement, the other for moving along the direction perpendicular to the film; both movements are performed on an electric axis.
Regarding the movement of translation in the direction of advancement of the film it is not possible to use a rod-crank mechanism since it has a fixed stroke and this means that, given a specific value of the film speed, it is not possible to vary the welding time; also a belt transmission is not advisable as it could be source of possible inaccuracies. Therefore a ball screw transmission is utilized. During the cycle of this axis, which continuously moves back and forth, the return stroke is obviously lost time, so it is important to make it as fast as possible: to this end, some manufacturers use linear synchronous motors. In fact, it is good to note that this type of motor allows to reach speeds up to 12 m/s (compared to 2 m/s of ball screws and 3-5 m/s of belt actuators), with maximum thrusts even over 10 kN; they also allow an improvement in the overall performance of the system thanks to the elimination of the kinematic chain, the increase in reliability, the elimination of inertias, backlash, elasticity and wear of the kinematic chain components; in spite of their exceptional performance, however, these actuators have not yet fully met the favor of packaging machine designers, also because of the high costs of permanent magnets.
For what concerns the movement along the direction perpendicular to the film, the big problem are the high forces that must be exerted by the welding jaws on the edges of the film. In particular, in some applications where high speeds are required (and therefore reduced welding times) and thick films are used (for instance, machines for the packaging of detergent wipes with 130 µm multilayer film and a required productivity of around 100 packages/min) it is possible to have to press with 10 kN of force, all repeated 100 times every minute. In these cases, from the design point of view the solution is not trivial at all.

In rotary or Long Dwell systems there are two rotating shafts that do not move (therefore it is not a problem to oversize them) and the welding jaws which, connected to the structure by springs, meet in interference and exchange a force depending only on the stiffness of the springs. In Box Motion systems, instead, it is necessary to use a double rod-crank mechanism controlled by a single motor; this solution has many more components compared to rotary and Long Dwell systems, with consequent wear problems.

Another factor to consider is the fatigue behavior which, in Box Motion welding systems, having a greater number of components, is more problematic. In food packaging it is of great importance to take into account the fact that 10 million cycles are carried out in 6-12 months, this leads to reasoning on fatigue behavior beyond the usual terms: Wohler curves, for instance, say that, in steels, at 5 millions of cycles the horizontal asymptote is reached but a component of a packaging machine must last 50 million cycles so it is essential to understand if it is really an asymptote.

Considering all three welding systems described above, it is possible to say that Box Motion is the system that offers greater flexibility thanks to the two degrees of freedom, the rotary system is the most performing system in terms of maximum productivity while the D-Motion guarantees a lower productivity compared to the rotary system but allows longer welding times given the same speed of the film. Moreover, Box Motion, compared to the other two welding systems, generally has a higher cost, lower dynamic performances (for instance, in the case of paper-based and difficult to weld films, on vertical machines it does not go beyond 80 packages/min), greater complexity of construction, greater risk of wear and implies greater vibrations as straight movements have more backlash.

In some situations, however, Box Motion offers considerable advantages, an example being the need to remove the air before closing the package. In these cases, normally there is a small air suction tube around which the tubular film is initially created, then, when the film advances, the tube gradually tends to come out of the pack and it is necessary to perform the last welding in the shortest time possible as soon as the tube come out, so as to do not let the air back in. Using a Box Motion system it is possible to implement a law of motion for the closure of the jaws so as to close the package but leaving a small slot and when the air has been removed the package is completely closed. A system like D-Motion has only one motor so it can never be as flexible as a Box Motion.

1.2.5 *Stand-Up Pouch* (or *Doypack*) *machines*

As anticipated at the start of this paragraph, stand-up pouch machines are machines in which the film advances horizontally while the product is loaded vertically (Fig. 34).

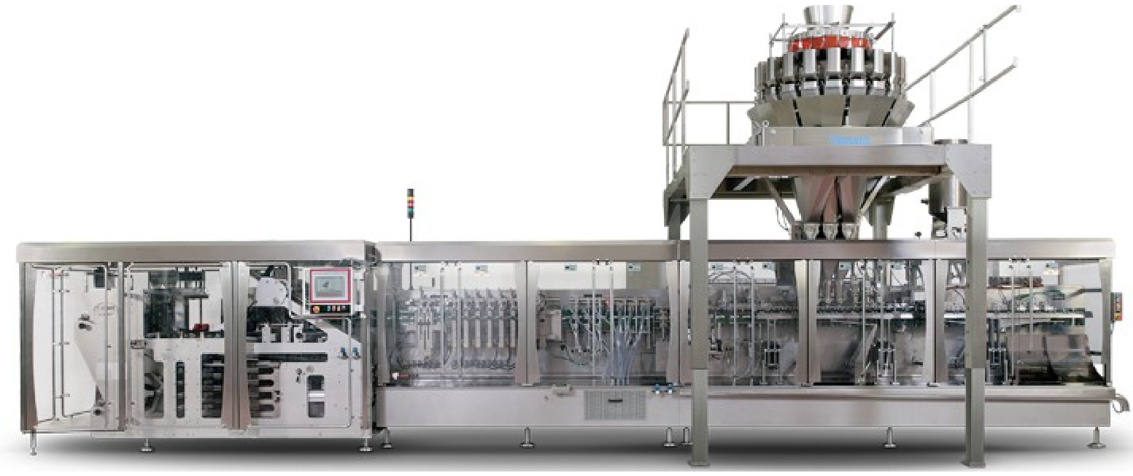

Figure 34: Example of a pouch machine [9].

Pouch machines are intermittent machines characterized by three important aspects:
- operation is subdivided over several processing stations placed one after the other;
- create, among others, “stand-up” bags, i.e. the standing alone bags (Fig. 35);
- realize the so-called "perfect” bag thanks to the dedicated processes carried out in the various stations.

In horizontal or vertical machines, the forming and filling of the bag are simultaneous processes, in stand-up pouch machines instead these two processes take place separately: in particular, the bag is first formed and then the filling takes place, all divided into different steps.

In general the process starts from the reel, the film is then folded into a bag shape, the first necessary holes are made, the bottom is welded, the side welds are made, the eventual closing zip is attached and at the end of these steps, performed in several work stations, an empty bag is obtained. At this point the bag is divided, through an appropriate cutting system, from the rest of the film (it is worth noting that while in the horizontal and vertical machines the bag is divided from the film when loaded with the product, in this case it is cut when it is still empty), then it is taken by a special transport system that makes it move along the machine, in this phase it is opened, filled with the product dosed with a multihead weigher, closed and finally the upper sealing is done.

Figure 35: Example of stand-up bags.

One of the pouch machine targets, as mentioned, consists in achieving the "perfect" bag: this is made possible by the operating principle of the machine, i.e. by the fact that the work is done on several stations. This structure allows, for example, to use up to 0.5 seconds for the welds (a time interval that is substantially higher than what is present in horizontal or vertical machines) thus allowing to seal well any type of film. Moreover there are a lot of possibilities in terms of aesthetics of the bag: in vertical machines, for instance, the bags always have straight edges, in pouch machines it is possible to make the edges flared (first doing the side welds and then modeling them with special cutting systems).

Furthermore, for what concerns weldings, usually two stages are provided, first the hot sealers to actually carry out the welding, then the cold sealers, in rubber and possibly water-cooled, to apply pressure again on the weld in order to eliminate the air bubbles; moreover, in this phase optional devices can be added, for example to round the corners, to make the eurohole or the diamond tear notch etc.

Another interesting aspect regards the tracking system that blows inert gas into the bags while transferring them: in pouch machines this system includes a first welding stage

(pre-sealer) which produces a very thin seal but in a short time, in order to prevent the gas escape, then the actual welding is done, followed by the cooling stage for an optimal aesthetics.
From the aforementioned it is clear that the pouch machine makes high quality bags, however there are some negative aspects: it is good to note the high price (at least 500'000 € compared to about 150'000 € of a vertical machine) and low productivity compared to the machine dimensions.
With regard to this last aspect, it is possible to say that normally a pouch machine achieves at most 60 cycles/min, corresponding to 60 bags/min if the machine produces a single pouch for each cycle. Therefore, the only way to increase the productivity of the machine consists in realizing the so-called "duplex", "triplex", or "quadruplex" machines, i.e. machines which, in each station, process two, three or four pouches at the same time, thus allowing to raise productivity up to 240 bags/min (in the quadruplex it is possible to manage a maximum of 110 mm wide pouches, otherwise at each cycle it would be necessary to pull an excessively long piece of film). The disadvantage of this type of machines, however, lies in the very large dimensions: as most of the stations grows in size as the number of bags that are processed in one cycle increases, it is possible to have quadruplex pouch machines up to 20 meters long.

1.3 Overview of primary food packaging films

Plastic materials are widely used in food packaging as they are used as components of laminated packaging films. Some reasons for the rapidly expanding use of plastics in packaging are their relatively low price, their easy processing, the possibility of modifying their properties, the good relation of weight to firmness, the possibility of thermal sealing, and the possibility of using them in combination with other packaging materials (aluminum, for instance).
Plastics can be used as they are or in a modification, but very often they are used in combination with other plastics or other materials, so as to enhance their properties or give them new properties. The plastics that are most common in food packaging are

polyethylene (PE), poly(vinylidene chloride) (PvdC), polypropylene (PP), polyesters (PET), polyamide (PA).

PE is one of the most common plastics, it is generally utilized as adhesive (lower melting point) coating in laminates and has two basic forms: high density (HDPE) and low density (LDPE). Both types can be heat-sealed (sealing temperature: 120-170 °C), and are suitable for shrink-wrapping. HDPE is 95% crystalline and can be used up to 120 °C, furthermore it presents low softening and melting points, good moisture barrier and poor oxygen barrier. LDPE is 60% crystalline and can be used up to 90 °C, furthermore it presents lower softening and melting point (good for heat-sealing), fair moisture barrier, very poor oxygen barrier and very high elongation (desirable for stretch wrap).

PE in general is cheaper than the other plastic films and has relatively good mechanical properties. LDPE is as strong as poly (vinyl chloride) (PVC) in impact stress, but it has a low tensile strength and is very soft. HDPE is stronger but more fragile than LDPE, it is also used in replacing multilayer paper bags especially when the product must be protected from moisture. Generally, stiffness, tensile strength, and chemical resistance of PE increase with density, but gas and vapor transmission, elongation, low-temperature impact strength and environmental crack resistance decrease when the PE density is increased, so LDPE is more suitable as sealing layer for food wrapping films. LDPE, however, presents problems in case of high-speed food packaging machines: its mechanical properties are not good enough to withstand the stress caused by welding jaws, which occur when the film is still cold (when the speed increases the phenomenon of mechanical stress is fast compared to thermal dynamics of the film); in this case there are forms such as Linear LDPE (LLDPE), or even LLDPE catalyzed with a metal, "Metallocene", (m-LLDPE): these forms present changes in molecular structure, compared to LDPE, such as to increase the mechanical properties and make them suitable for high-speed packaging (Fig. 36). It is important to underline the importance of this last aspect as the mechanical characteristics of the film sealing layer represent a fundamental factor in the design phase of food packaging machines.

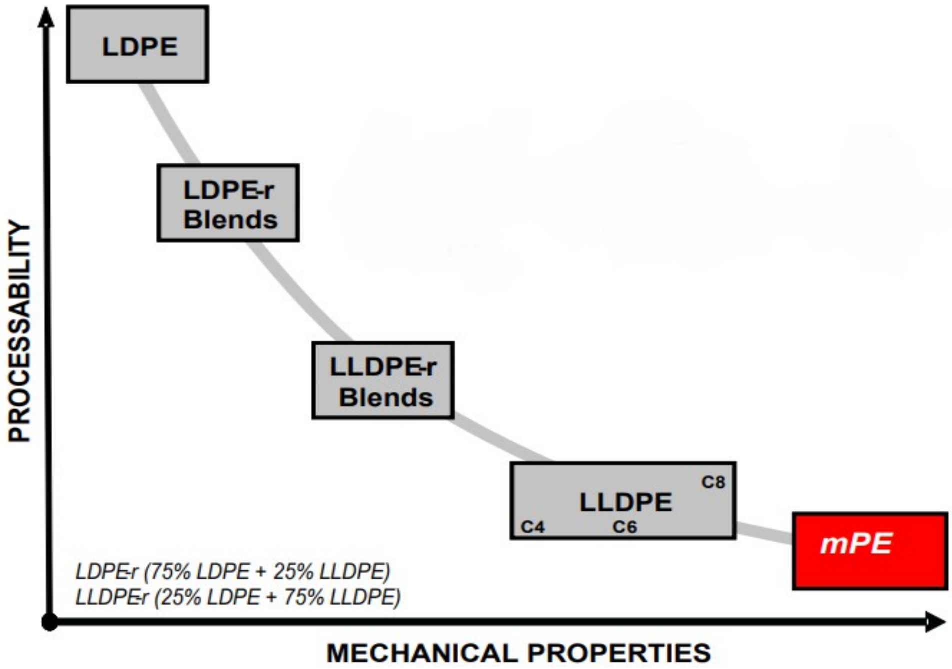

Figure 36: Processability vs Mechanical properties of PE forms.

Polyvinylidene chloride (PVdC) has low moisture and gas permeability. It is a little less elastic than PE and is an odor barrier. In packaging, it is much used because of its good stress-crack resistance. PVdC shrinks at relatively low temperatures, but at 150-170 °C it shrinks about 30%. Due to its low moisture, gas and odor permeability, it is widely used in wrapping many foods, or as gas and moisture barrier in multilayer films. Its use is extended from frozen products to fresh and dried food. PVdC is also used in vacuum packaging and in coating other materials. PVdC, like PE, is used as moisture barrier and in sealing packages that are made of materials that cannot be heat-sealed. However, since PE is cheaper, it is mostly preferred where gas tightness is also required.

Polypropylene (PP) has about the same elasticity as PVdC. Its tensile strength is four times that of PE and it is very widely used as a flexible packaging material. The low-density PP is a good moisture barrier, but it is permeable to many gases and air; furthermore oriented PP (OPP) and bi-oriented PP (BOPP) films are clear, stiff and glossy whereas unoriented PP becomes brittle at low temperatures. It is important to note that film orientation consists of stretching the film in one (monoaxial, e.g. OPP) or two (biaxial, e.g. BOPP) directions in order to dramatically improve properties such as stiffness, tensile strength and yield in general while reducing elongation.

Polyesters (PET) have significant tensile strength in a wide range of temperatures (from -60 °C to 150 °C); moreover they are good moisture, gas and aroma barrier. They are very often used for beverage containers. Finally PET is used externally as film in laminates with PE.

Polyamide (PA) is a strong material and its tensile strength is three times that of PE and one-third that of PET, and it is ten times harder than PE. The PA known as "nylon" is a good water barrier and has a low gas permeability (comparable to that of PET). It can be used at temperatures between -40 °C and above 100 °C (the melting point of nylon is 215 °C). Therefore, it can be used for boil-in bags or where the packed products will be thermally processed. Furthermore there exist the oriented forms of PA films (OPA, BOPA) which presents better mechanical characteristics.

Poly(tetrafluoroethylene) (PTFE), known also as Teflon, is very heat resistant, has a very low coefficient of friction, has nonadhesive properties, and is chemically inert. It can be used at temperatures up to 230 °C. However, since it is expensive, it is used only in connection with heat-resistant coatings of containers that are reused, and where stickiness must be avoided. A common use in packaging technology is the PTFE-coating of the heat sealing elements.

For what concerns the plastic-based films which are utilized in food packaging, they can be manufactured in two different ways:

- Mono layer films: a single layer of material often with an adhesive (lower melting point) coating. Different coatings used include as an example PE, in particular its low density forms, such as LDPE, LLDPE, m-LLDPE.
- Laminates (Fig. 37): multilayer films formed from two or more different substrate materials (packaging laminate plies are listed from the outside to the inside).

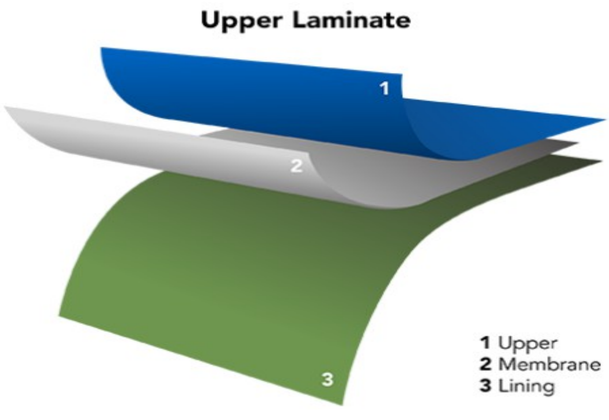

Figure 37: Schematic view of a laminate film with 3 layers.

The sealant layer is dictated by the material, the type of seal needed (e.g., weld or peel) and especially the speed of the machine. Laminates assemble materials with individually desirable properties to create an optimum combination and in general this applies not only to plastics materials: as an example aluminum layers are also used in order to create a barrier to all gases, moisture and light (Fig. 38); OPP, PET and PA (nylon) are the most commonly metallized packaging films (a thin aluminum layer, around 7 μm, can improve Oxygen barrier up to fifty times for OPP, up to ten times for PET).

Figure 38: PP / Al / LDPE laminate ready for installation on a pouch machine.

1.4 Flexibility in primary food packaging

Up to ten years ago in the food packaging industry a wrapping machine which was able to seal a specific type of package at the predefined productivity level was ok, today a machine with such characteristics would be not good enough. Customers nowadays are looking for machines which can guarantee good flexibility (namely the differences in the dimensions of feasible packages) together with production volumes higher than before. These requirements are not trivial to obtain since in general it is difficult, for high production machines, to manage a wide range of highly diversified goods as well as it is not easy, for flexible machines, to reach high production levels. Moreover, considering that one or more format changes can be made per day, it is essential that the machines are as self-configurable as possible and that the entire format change process requires a limited time, generally a few minutes.

In order to obtain these results, the "servo" machines are becoming more and more popular, i.e. machines where the axes are electric axes, so implemented through brushless motors; these motors, in fact, generally guarantee excellent dynamic performances: high torque to weight, torque to volume and torque to current ratios together with a bandwidth for the speed control loop that can reach 250 Hz well adapt to the industrial automation and in particular to food packaging machines, where high dynamic performances are required.

Moreover, the abrupt variations in speed required by machines both for the high productivity, which translate into large accelerations and therefore required torques to the engines, and to allow the production of many different product formats lead to the need of using carefully chosen gearboxes.

For what concerns Delta robotics in food packaging lines, to further increase flexibility, a robot cell can be configured with multiple arms for both feed placing and top loading functions, utilizing a single controller. In addition, both functions can be programmed with vision systems and advance tracking, capable of picking and loading moving targets.

Most robot manufacturers incorporate flexibility into their machines, such as the ability to use different types of end-effectors. This is critical when packaging requires going from a single pick to a multi-pick or packaging another product type.

Another type of flexibility is the option to add or change recipes within the software programs, which control the arm of the robot, whether there is one or multiple arms in the robot cell. The ease in which the software allows a user to create recipes for new products, or optimize existing processes, is an important criteria in selecting a robot that provides flexibility over the length of the investment. State-of-the-art software now enables users to visualize the picking process in 3 dimensions on the HMI (human machine interface) and provides a precise view of robot movements in real time. This makes diagnosing errors of missed products or sensor malfunctions straight forward, and optimizing pick-and-place patterns intuitive. Similarly, software that allows new recipes to be simulated in 3D in a virtual production environment without running product ensures new recipes achieve the required performance prior to test runs.

CHAPTER 2

THE SELECTION OF THE MOTOR-REDUCER UNIT: AN INNOVATIVE APPROACH

The aim of this chapter is to focus on the motor-reducer unit selection and on what this implies for an automatic machine. In the first paragraph an innovative approach is introduced which consists in a practical methodology for the correct sizing of the motor-reducer coupling [10, 11]. In the second paragraph an example about an horizontal flow-wrapping machine is shown to demonstrate the advantages of designing a motor-reducer couple with the approach exposed in the first paragraph [12]. Finally, in the third paragraph some improvements are proposed in order to consider those aspects which are fundamental for a correct choice of the reducer but have been ignored in the previous two paragraphs [13, 14, 15, 16].

2.1 The innovative approach

In industrial automation it is common to describe a generic machine axis as a group composed by four components: electric drive, electric motor, transmission and load (Fig.39). Usually all the parameters related to the load are fully known as they depend on the task while the motor, drive and transmission characteristics have to be selected.

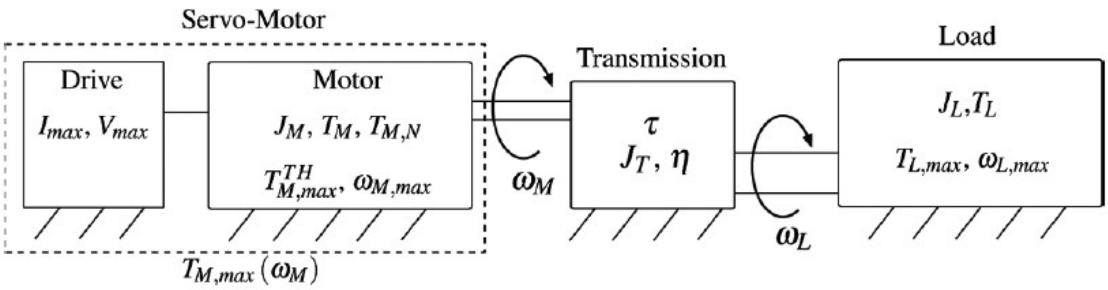

Figure 39: Model of a generic machine axis [9].

It is convenient to introduce the following Tab. 1 which contains the meaning of the most important symbols used in this chapter.

Symbol	Description
T_M	Motor torque
J_M	motor moment of inertia
$T_{M,rms}$	Motor root mean square torque
$T_{M,N}$	Motor nominal torque
$T_{M,max}^{TH}$	Motor theoretical maximum torque
$T_{M,max}$	Servo-motor maximum torque
ω_M	Motor angular speed
$\dot{\omega}_M$	Motor angular acceleration
T_L	Load torque
J_L	Load moment of inertia
T_L^*	Generalized load torque
$T_{L,rms}^*$	Generalized load root mean square torque
$T_{L,max}$	Load maximum torque
ω_L	Load angular speed
$\dot{\omega}_L$	Load angular acceleration
$\dot{\omega}_{L,rms}$	Load root mean square acceleration
$\tau = \omega_L/\omega_M$	Transmission ratio
τ_{opt}	Optimal transmission ratio
η	Transmission mechanical efficiency
α	Accelerating factor
β	Load factor
τ_{min}	Minimum acceptable transmission ratio
τ_{max}	Maximum acceptable transmission ratio
$\tau_{M,lim}$	Minimum kinematic transmission ratio (defined for each motor)
$\omega_{M,max}$	Maximum speed achievable by the motor
$\omega_{L,max}$	Maximum speed achieved by the load
J_T	Transmission inertia
t_a	Cycle time

Table 1: Nomenclature [9].

The generic equation of the motor torque is:

$$T_M = (J_M + J_T)\dot{\omega}_M + \frac{\tau}{\eta}(J_L \dot{\omega}_L + T_L) \qquad (1)$$

so, as it depends on the acceleration and eventually on the speed (if T_L comprehends a term proportional to the speed, a viscous contribute for example), the choice of a proper law of motion is the first project parameter that should be taken into account when sizing the motor-reducer unit. In order to choose the law of motion that suits the application requirements the most there are various aspects that should be considered, as for example the maximum velocity reached during the motion period (every motor and transmission have their own speed limits), the maximum acceleration (could generate problems on the load or exceed the torque limits of the motor or the transmission), the root mean square acceleration value (if minimized, in case of mostly inertial load this will reduce the size of the motor needed), the total energy consumption (for example in battery supplied applications), the smoothness (in case of vibration issues for the specific application) and so on; for this purpose, specific texts are available. Otherwise, it may be that the law of motion has already been defined and therefore represents a problem datum and not a project variable. Anyway, once the law of motion is defined, all the characteristics of the load are fully known.

For what concerns the motor, brushless motors are the most common electrical actuators in industrial automation field. In Fig. 40 it is possible to see a typical working range for this type of motors and it is divided into two main areas:

- the highlighted area represents the continuous working zone, which comprehends all the conditions where the motor can work for an infinite time without overheating
- the area delimited by the dashed line represents the maximum limits of the motor, which comprehends all the conditions where the motor can work but for a finite time, otherwise it will suffer overheating; this zone is usually restricted because of the limits of the drive unit (in terms of maximum current where the limit is an horizontal line and maximum voltage where the limit is a decreasing line).

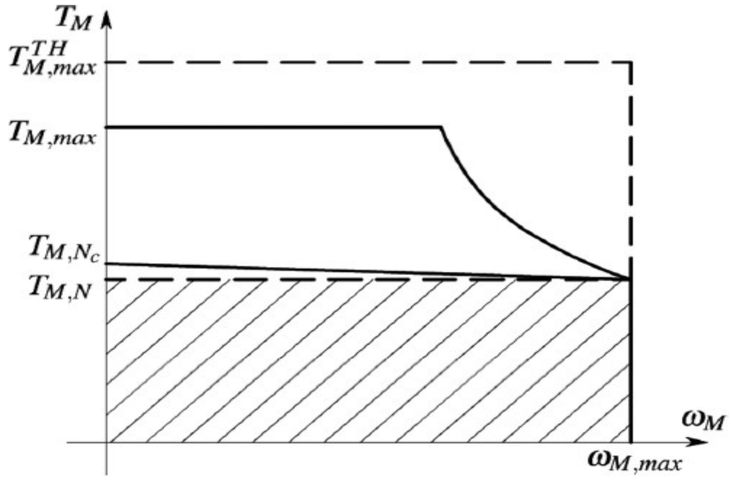

Figure 40: Generic brushless motor working range [9].

Furthermore, another important parameter is the rated torque, which is the torque limit between the continuous working range and the area above: usually the limit value is not the same from 0 to $\omega_{M,max}$ but in [10] it is said that, given the fact that the difference between $T_{M,Nc}$ and $T_{M,N}$ is often limited, it is possible to consider the value $T_{M,N}$ as a constant.

Frequently, in industrial applications, the machine task is cyclical with a period t_a which is normally much smaller than the motor thermal time constant: in this case the motor behavior can be analyzed through the root mean square value of T_M, defined as

$$T_{M,rms} = \sqrt{\frac{1}{t_a}\int_0^{t_a} T_M^2\, dt} \qquad (2)$$

that is the torque, acting steadily over the cycle, which is attributable to the total energy dissipation that actually occurred in the cycle.

As it has been decided to consider the rated torque as a constant value, $T_{M,N}$, the conditions that have to be checked in order to select the proper motor are three: a condition on the rated motor torque, which has to be greater than the motor root mean square torque, a condition on the maximum motor angular speed, which has to be greater than the angular speed needed by the application, and finally a condition on the maximum servo-motor torque, which has to be greater than the motor torque needed by the application. It is possible to summarize these three constraints as the followings:

$$T_{M,rms} \le T_{M,N} \qquad (3)$$

$$\omega_M \le \omega_{M,max} \qquad (4)$$

$$T_M(\omega_M) \le T_{M,max}(\omega_M) \qquad (5)$$

The terms on the right side of inequalities (3), (4), (5) are characteristic of each motor. On the other hand the terms on the left side depend on the load and, therefore, on the reducer transmission ratio τ. During the choice of the reducer it is important to consider many factors as the maximum generalized load torque (that is the maximum value of the overall torque at the slow shaft), the maximum angular speed, the mean generalized load torque and the mean angular speed; furthermore the moment of inertia and the efficiency of the transmission have to be taken into account; anyway, in [10], the approach is to verify the constraints and the non idealities of the reducer only after the best candidate has been selected in order to improve the practicality of the method.

Considering what is written above it is possible to neglect J_T (J_T = 0 [Kgm^2]) and η_T (η_T=1) and so equation (1) becomes

$$T_M = J_M \dot{\omega}_M + \tau T_L^+ = J_M \frac{\dot{\omega}_L}{\tau} + \tau T_L^+ \quad (6)$$

where

$$T_L^+ = T_L + J_L \dot{\omega}_L \quad (7)$$

represents the generalized load torque.

From equation (2) it is possible to obtain the expression of the root mean square torque:

$$T_{M,rms}^2 = \int_0^{t_a} \frac{T_M^2}{t_a} dt = \int_0^{t_a} \frac{1}{t_a} \left(\tau T_L^+ + J_M \frac{\dot{\omega}_L}{\tau} \right)^2 dt \quad (8)$$

and then

$$T_{M,rms}^2 = \tau^2 T_{L,rms}^{+2} + J_M^2 \frac{\dot{\omega}_{L,rms}^2}{\tau^2} + 2 J_M (T_L^+ \dot{\omega}_L)_{mean} \quad (9)$$

Combining inequality (3) and equation (9) the result is

$$\frac{T_{M,N}^2}{J_M} \geq \tau^2 \frac{T_{L,rms}^{+2}}{J_M} + J_M \frac{\dot{\omega}_{L,rms}^2}{\tau^2} + 2 (T_L^+ \dot{\omega}_L)_{mean} \quad (10)$$

At this point it is possible to define two parameters, α and β, by which the designer can quickly obtain useful information to make an initial selection of all the potentially available solutions in terms of motor-reducer couplings.

Parameter α, also called *accelerating factor*, is defined as

$$\alpha = \frac{T_{M,N}^2}{J_M} \quad (11)$$

and describes the performances of each motor.

Parameter β, also called *load factor*, is defined as

$$\beta = 2 [\dot{\omega}_{L,rms} T_{L,rms}^+ + (\dot{\omega}_L T_L^+)_{mean}] \quad (12)$$

and expresses the performance required by the task. The unit of measurement of both factors is [W/s] so they are comparable. Furthermore the coefficient α is exclusively defined by parameters related to the motor and therefore it does not depend on the machine's task and can be easily calculated using the information provided in the manufacturer catalogs; otherwise, the coefficient β depends only on the working conditions (applied load and law of motion) and is a measure that defines the power rate required by the system.

Substituting α and β in inequality (10) the result is

$$\alpha \geq \beta + \left[T^{+}_{L,rms}\left(\frac{\tau}{\sqrt{J_M}}\right) - \dot{\omega}_{L,rms}\left(\frac{\sqrt{J_M}}{\tau}\right)\right]^2 \quad (13)$$

Inequality (13) shows that the suitability of a motor depends on the speed ratio τ. In fact, the term in brackets is always positive and becomes null for a specific value of τ which is

$$\tau = \tau_{opt} = \sqrt{\eta_T (J_M + J_T)\frac{\dot{\omega}_{L,rms}}{T^{+}_{L,rms}}} \quad (14)$$

Considering the ideality hypothesis for the transmission, equation (14) becomes

$$\tau = \tau_{opt} = \sqrt{J_M \frac{\dot{\omega}_{L,rms}}{T^{+}_{L,rms}}} \quad (15)$$

β thus represents the minimum value of inequality (13) and this means that, for each potentially usable motor, the necessary but non sufficient condition to be satisfied is $\alpha_i \geq \beta$. It is also clear that the higher is α_i compared to β the greater the range of gear ratios satisfying the constraint on motor rated torque will be. This range can be calculated by solving the biquadratic inequality (13), which leads to

$$\left(\frac{T^{+2}_{L,rms}}{J_M}\right)\tau^4 + (\beta - \alpha - 2T^{+}_{L,rms}\dot{\omega}_{L,rms})\tau^2 + J_M \dot{\omega}_{L,rms}{}^2 \leq 0 \quad (16)$$

which in turn has four different real solutions. As the direction of the rotation is not of interest, only the positive values of τ are considered:

$$\tau_{min} \leq \tau \leq \tau_{max} \quad (17)$$

with

$$\tau_{min}, \tau_{max} = \frac{\sqrt{J_M}}{2T^{+}_{L,rms}}[\sqrt{\alpha - \beta + 4\dot{\omega}_{L,rms}T^{+}_{L,rms}} \pm \sqrt{\alpha - \beta}] \quad (18)$$

The range width depends on the difference between α and β according to the equation

$$\Delta\tau = \frac{\sqrt{J_M}}{T^+_{L,rms}}\sqrt{\alpha-\beta} \qquad (19)$$

where it is clear that if $\alpha = \beta$ the only gear ratio allowed is τ_{opt}.

Furthermore there is another constraint to consider when evaluating the minimum available value of τ and it depends on both the maximum achievable speed of the motor ($\omega_{M,max}$) and the maximum speed of the load ($\omega_{L,max}$)

$$\omega_{L,max} \leq \tau\omega_{M,max} \qquad (20)$$

Therefore for every motor we can derive a condition on the minimum τ

$$\tau \geq \tau_{M,\lim} = \frac{\omega_{L,max}}{\omega_{M,max}} \qquad (21)$$

Finally the range width is

$$\tau_{max} \geq \tau \geq max(\tau_{min};\tau_{M,\lim}) \qquad (22)$$

Now it is possible to summarize all the procedure in some steps also using graphs which make the selection process easy to use (the following graphs refer to an example application):

- *Step 1*: creation of a database containing all the commercially available motors and reducers useful for the application; then the parameter α has to be evaluated for each motor. Once the database has been completed it can be re-used and eventually updated each time a new selection of a motor-reducer unit is needed.
- *Step 2*: calculation of the load factor β for the specific application.
- *Step 3*: make a preliminary choice of available motors by comparing only α and β: all the motors for which $\alpha < \beta$ have to be rejected, the others can be considered for the next step because they can have enough rated torque if the speed ratio is chosen properly. A graphical example regarding this step can be seen in Fig. 41, where some motors (M1 - M11) for a specific application are represented in the x-axis whereas in the y-axis all the α_i parameters and β are shown; in this case motors M1, M2 and M7 have to be discarded.
- *Step 4*: identification of the ranges of useful transmission ratios for each motor preliminarily selected in step 3. For these motors a new graph is produced, in Fig. 42, displaying, for each of them, the value of the transmission ratios τ_{max}, τ_{min}, τ_{opt}, and $\tau_{M,lim}$;

furthermore, this graph is usually drawn using a logarithmic scale for the y-axis, so that τ_{opt} is always the midpoint of the adoptable transmission ratios range.

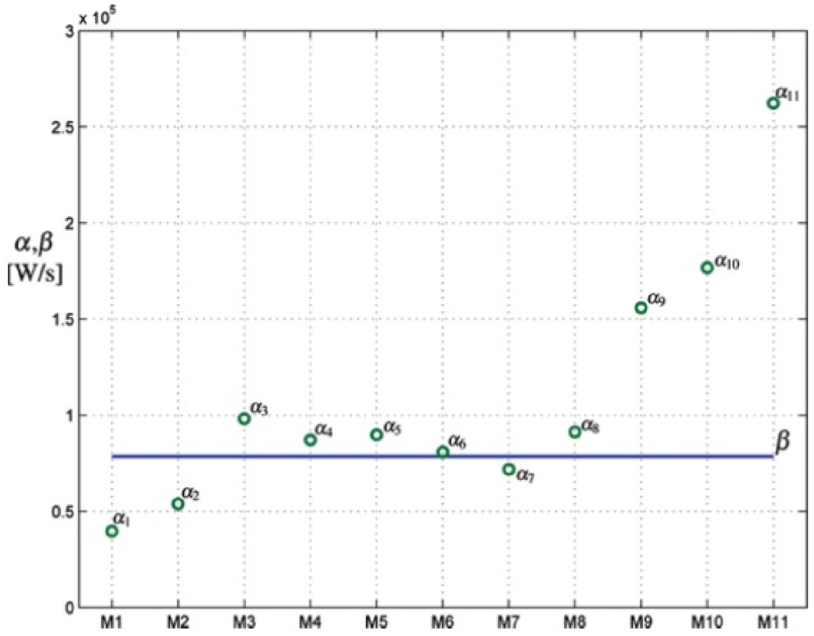

Figure 41: Comparison between the accelerating factors of each considered motor (α_i) and the load factor (β) for an example application [9].

In fact

$$\tau_{opt}^2 = \tau_{min}\,\tau_{max} \quad iff \quad \log\tau_{opt} = \frac{\log\tau_{min} + \log\tau_{max}}{2} \qquad (23)$$

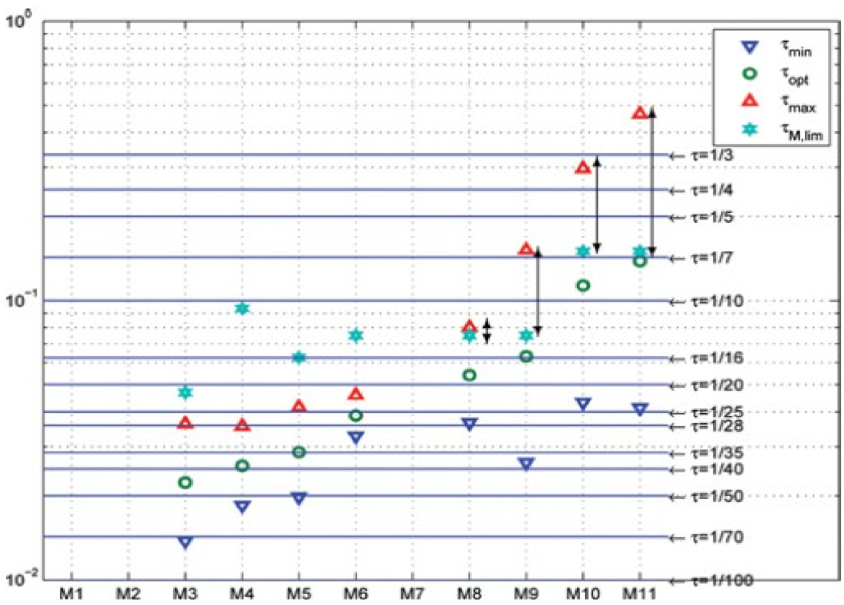

Figure 42: Overview of available motor-reducer couplings for an example application[9]

A motor is acceptable if there is at least a transmission ratio τ for which equation (22) is verified. These motors are highlighted by a vertical line in Fig. 42.

- *Step 5*: identification of commercial speed reducers which verify equation (22): all the available speed reducers are represented by horizontal lines, if one of them intersects the vertical line of a motor, this means that the motor can supply the required torque if that specific speed reducer is selected. Tab. 2 sums up, with regards to the graph in Fig. 42, the acceptable combination of motors and speed reducers: these ones are admitted to the final selection phase.

Motor	Speed reducer
M9	$\tau = 1/10,\ \tau = 1/7$
M10	$\tau = 1/5,\ \tau = 1/4$
M11	$\tau = 1/5,\ \tau = 1/4,\ \tau = 1/3$

Table 2: Combination of suitable motors and gearboxes for an example application [9].

- *Step 6*: optimization of the selected alternatives: the selection can be completed using some criteria as economy, overall dimensions, space availability and so on.

It is important to note that up to here, in this approach [10], the mechanical constraints of the speed reducers have not been considered yet: for example, in Tab. 2, only the available gear ratios are shown but at this point it is not possible to say weather the relative speed reducers are really suitable or not.

- *Step 7*: checks. This is the final step, where the moments of inertia J_M, J_T, the transmission mechanical efficiency η and the gear ratio τ are known for each motor-reducer couple.

In general it is possible to define W_M and W_L, respectively, as the power upstream and downstream of the transmission. When the power flows from the motor to the load it is said that the machine works with *direct power flow*, the process is described as *reverse* otherwise. Transmission power losses are different in the two cases and so they are described by two different mechanical efficiency values, $\eta_d \leq 1$ and $\eta_r \leq 1$. To unify these different operating conditions a general mechanical efficiency function is introduced, where η, η_d and η_r are considered constant values:

$$\eta(t) = \begin{cases} \eta_d & if \; W_r > 0 \; (direct\ power\ flow\ functioning) \\ \dfrac{1}{\eta_r} & if \; W_r < 0 \; (reverse\ power\ flow\ functioning) \end{cases} \qquad (24)$$

Knowing J_T and η leads to some changes in aforementioned formulas, in particular equation (6) becomes

$$T_M = (J_M + J_T)\dot{\omega}_M + \frac{\tau}{\eta} T_L^+ = (J_M + J_T)\frac{\dot{\omega}_L}{\tau} + \frac{\tau}{\eta} T_L^+ \quad (25)$$

Now it is possible to check the following constraints:

- the maximum torque supplied by the servo-motor for each angular speed achieved:

$$T_{M,max}(\omega_M) \geq max\left|(J_M + J_T)\frac{\dot{\omega}_L}{\tau} + \frac{\tau}{\eta} T_L^+\right| \qquad (26)$$

- the effect of the transmission mechanical efficiency, η, and its moment of inertia, J_T,on the root mean square torque: in order to calculate $T^2_{M,rms}$ we can utilize the following equation:

$$T^2_{M,N} \geq T^2_{M,rms} = \int_0^{t_a} \frac{T_M^2}{t_a} dt = \int_0^{t_a} \frac{1}{t_a}\left((J_M + J_T)\frac{\dot{\omega}_L}{\tau} + \frac{\tau T_L^+}{\eta}\right)^2 dt \qquad (27)$$

- the mechanical limits of the reducer as indicated on the catalog by the manufacturer.

At this point it can be interesting to focus on what the transmission mechanical efficiency implies for both the motor and reducer selection. Considering machines working with direct power flow, the equivalent mechanical efficiency of the transmission ($\eta \leq 1$) cause a power dissipation which can make the motor non longer adequate: this is because in the first six steps of the described procedure the presence of η in the transmission was not considered.

To see why η influences the choice of motor and transmission it can be noted that inequality (13) becomes

$$\alpha \geq \frac{\beta}{\eta} + \left[\frac{T^+_{L,rms}}{\eta}\left(\frac{\tau}{\sqrt{J_M}}\right) - \dot{\omega}_{L,rms}\left(\frac{\sqrt{J_M}}{\tau}\right)\right]^2 \qquad (28)$$

and the biquadratic inequality (16) to solve in order to find the range of useful transmission ratios becomes

$$\left(\frac{T_{L,rms}^{+2}}{\eta^2 J_M}\right)\tau^4 + \left(\frac{\beta}{\eta}-\alpha-\frac{2T_{L,rms}^{+}}{\eta}\dot{\omega}_{L,rms}\right)\tau^2 + J_M\,\dot{\omega}_{L,rms}{}^2 \le 0 \qquad (29)$$

Inequality (17) ($\tau_{min} \le \tau \le \tau_{max}$) is still valid but the two positive solutions of the (29) are now expressed by

$$\tau_{min},\tau_{max} = \eta\frac{\sqrt{J_M}}{2T_{L,rms}^{+}}\left[\sqrt{\alpha-\frac{\beta}{\eta}+\frac{4\dot{\omega}_{L,rms}T_{L,rms}^{+}}{\eta}}\pm\sqrt{\alpha-\frac{\beta}{\eta}}\right] \qquad (30)$$

Finally equation (15) becomes

$$\tau=\tau_{opt,\eta}=\sqrt{\eta J_M\frac{\dot{\omega}_{L,rms}}{T_{L,rms}^{+}}}=\tau_{opt}\sqrt{\eta} \qquad (31)$$

Therefore, referring to inequality (28), a motor which is able to perform the planned task in ideal conditions (η=1) could be discarded when coupled with a transmission characterised by poor efficiency. Furthermore, referring to equation (30), it can be seen that once β is known, for each motor (and so for each α) a minimum transmission equivalent mechanical efficiency exists below which τ_{min} and τ_{max} are undefined since radicands have to be non-negative. The limit value is called the transmission *mechanical efficiency limit* and it is defined as

$$\eta \ge \eta_{lim} = \frac{\beta}{\alpha} \qquad (32)$$

This parameter allows the designer to know, given the values of α and β for the specific application, what is the minimum value of the transmission's mechanical equivalent efficiency below which the system can not work (this limit is not present in the case of reverse power flow functioning).
When the characteristics of the load (β) and the motor (α) are known it is also possible to graphically represent, for each motor, the trend of both τ_{min} and τ_{max} as functions of η with the following equations:

$$\tau_{min} = \eta\frac{\sqrt{J_M}}{2T_{L,rms}^{+}}\left[\sqrt{\alpha-\frac{\beta}{\eta}+\frac{4\dot{\omega}_{L,rms}T_{L,rms}^{+}}{\eta}}-\sqrt{\alpha-\frac{\beta}{\eta}}\right] \; if\; \eta \ge \eta_{lim} \qquad (33)$$

$$\tau_{max} = \eta \frac{\sqrt{J_M}}{2T^+_{L,rms}} \left[\sqrt{\alpha - \frac{\beta}{\eta} + \frac{4\dot{\omega}_{L,rms} T^+_{L,rms}}{\eta}} + \sqrt{\alpha - \frac{\beta}{\eta}} \right] \ \mathit{if}\ \eta \geq \eta_{\lim} \quad (34)$$

$$\tau_{min}, \tau_{max} = \mathit{undefined} \ \ \mathit{if}\ \eta < \eta_{\lim} \quad (35)$$

so highlighting a region in the plane η-τ satisfying the condition on the root mean square torque (Fig. 43).

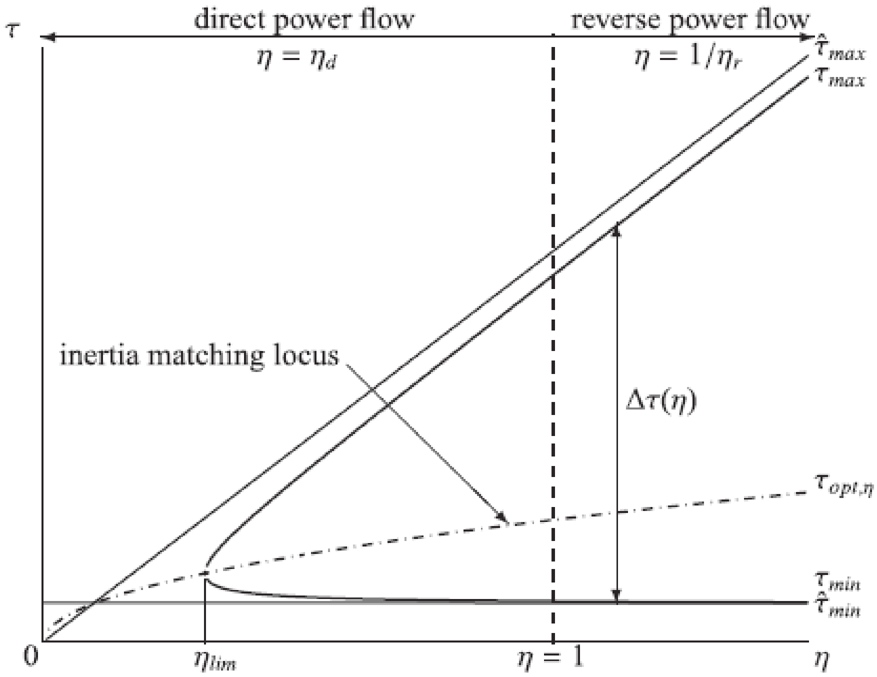

Figure 43: Trends of τ_{min} and τ_{max} with respect to η for a specific motor [10].

In this graph it is also possible to see the trends of τ_{opt} and the range of Δτ with respect to η where in particular Δτ increases with the difference between α and β and decreases with η, according to the equation

$$\Delta\tau(\eta) = \frac{\sqrt{J_M}}{T^+_{L,rms}} \eta \sqrt{\alpha - \frac{\beta}{\eta}} \quad (36)$$

Furthermore the equations of the asymptotes are

$$\hat{\tau}_{max} = \frac{T_{M,N}}{T^+_{L,rms}} \eta \quad (37)$$

$$\hat{\tau}_{min} = \frac{J_M}{T_{M,N}} \dot{\omega}_{L,rms} \quad (38)$$

and it is worth noticing that the minimum transmission ratio remains almost constant with respect to η. It is also interesting to observe that, while $\hat{\tau}_{max}$ depends on the reducer, $\hat{\tau}_{min}$ depends only on the chosen motor and on the law of motion defined by the task. This is because the transmission ratio τ is so small that the effect of the load is negligible compared to the inertia of the motor. The power supplied, therefore, is used just to accelerate the motor itself. Finally it is important to consider the fact that for values of $\eta > 1$, that is reverse power power flow functioning, the range of suitable transmission ratios is wider than in the case of direct power flow functioning, which is the most restrictive working mode. For this reason, in case the working mode during the operative cycle is not mainly either direct or revers it is better to design the motor-transmission couple considering the power flow as mainly direct, in a precautionary manner.

In the end it is useful to define the *extra-power rate factor* (γ): this factor comes from inequality (28), which can be written as

$$\alpha \geq \frac{\beta}{\eta} + \gamma(\tau, \eta, J_M) \qquad (39)$$

where

$$\gamma(\tau, \eta, J_M) = \left[\frac{T^{+}_{L,rms}}{\eta} \left(\frac{\tau}{\sqrt{J_M}} \right) - \dot{\omega}_{L,rms} \left(\frac{\sqrt{J_M}}{\tau} \right) \right]^2 \qquad (40)$$

The *extra-power rate factor* represents the additional power rate that the system requires if the transmission ratio is different from the optimum value.

In Fig. 44 are represented the trends of the terms of the γ function and the γ function itself with respect to the values of τ and η: the graph shows that when the transmission ratio is equal to the optimum value the curve γ assumes its minimum value (in particular, by definition of τ_{opt}, $\gamma(\tau = \tau_{opt}) = 0$). With the mechanical efficiency decreasing two effects take place: it is possible to see both a reduction in the value of the optimum transmission ratio and a more pronounced convexity of the curve γ. This last aspect is very important because it means that the system is more sensitive to changes in the value of τ with respect to the optimum: it is clear hence that for transmissions characterised by poor mechanical efficiency, in the case of the direct power flow mode, the choice of a gear ratio different from the optimum significantly affects the choice of the motor.

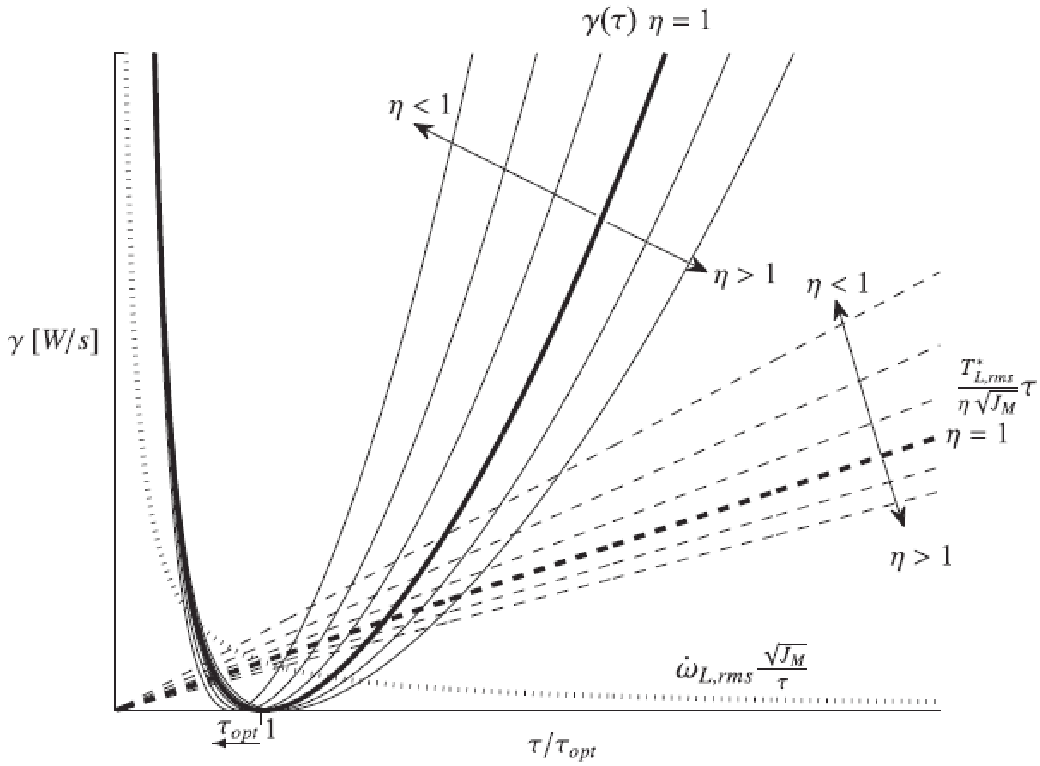

Figure 44: Variation of the extra-power rate factor as a function of the transmission ratio and mechanical efficiency [11].

2.2 Example: an horizontal wrapping machine

2.2.1 *Introduction*

In this paragraph it is shown, with regard to an horizontal wrapping machine, how the method previously exposed permits not only to have a more practical approach in the motor-reducer selection but also to maximize the performances of the machine in terms of flexibility and high production volumes.
About the end sealer mechanism, in this example the machine is equipped with a rotary sealing system which is composed by a couple of rotating heads. On their external circumferences, *N* tools are mounted with the double purpose to weld and cut the packages. In fact, each tool is constituted by a central saw profile in order to cut each package whose ends are simultaneously welded by heat-seals units fitted on the side of the saw profile.

Each package is composed by three parts, as shown in Fig. 45: two welded terminals, whose length is $L_T/2$, and the central part, whose length is $L_{P,a}$; the product length is L_P.

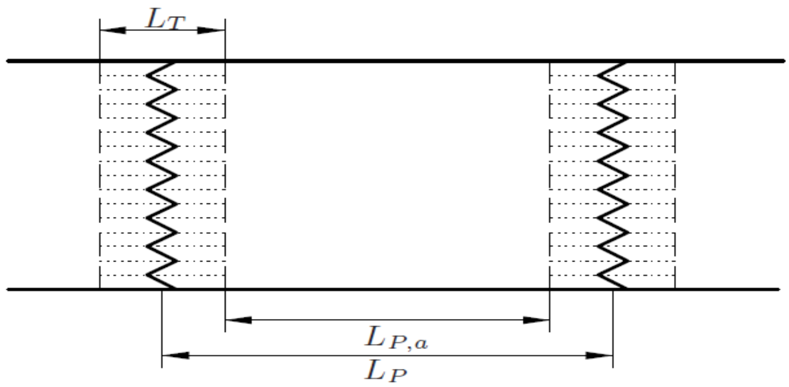

Figure 45: Package dimensions [12].

The most suitable working condition for a rotary sealing system is to have a constant angular speed in order to have negligible dynamic loads so it is useful to choose, together with the customer, a “base” length (that is the length of the most common package the machine will have to produce, L_0) to optimize the machine performance in this configuration; in every other case, if the product length is different from the design one, acceleration or deceleration are required in order to account for the imposed target product length. Thus, the radius R_t of the rotating head (Fig. 46) is designed, keeping in mind the layout constraints of the machine, in order to obtain a circumference which length is proportional to L_0, such that $2\pi R_t = NL_0$, where the integer ratio $N = 2\pi R_t / L_0$ corresponds to the number of cutting tools to be installed onto the rotating heads.

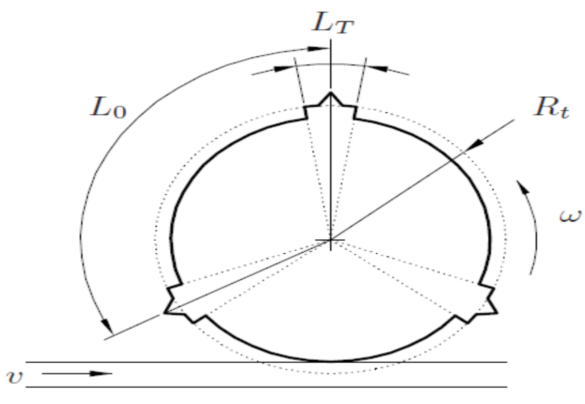

Figure 46: Cutting tool parameters [12].

2.2.2 *Motion characteristics*

In order to meet the productivity P of a generic product with length L_P, the belt conveyor has to maintain a constant speed equal to $v = L_P P/60$, where P is expressed in pieces min^{-1}.

The cycle time is defined as $T = 60/P = T_t + T_a$ where T_t is the time duration of the cutting phase, that is the part of the cycle dedicated to weld and cut the packaging of the product and T_a is the time duration of the approaching phase, that is the time from the finish of a cut and the beginning of the next one.

During the cutting phase the tangential velocity of the rotating heads have to be equal to the one of the belt conveyor (v) in order to have a null relative speed between them. The belt conveyor velocity can also be expressed as $v = L_t/T_t$ and so the angular speed of the rotating heads during the cutting phase is $\omega_t = v/R_t = L_t/(R_t T_t)$

Usually Lt is not a design parameter for the law of motion because it is imposed by the dimension of the cutting tools and this is typically defined by the customer.

During the approaching phase, if $L_P = L_0$ then the angular velocity of the rotating heads (ω_a) will be equal to ω_t. If $L_P \neq L_0$ then the angular velocity of the rotating heads during the approaching phase must increase or decrease to properly place the tool for the next cutting phase; therefore it is possible to say that $\omega_a = \omega_t + \Delta\omega$ where $\Delta\omega$ represents the variation of angular speed needed to get the tools in the correct position to execute the next cut. Two conditions therefore can be reached: $L_P < L_0$, in this case the rotating heads must accelerate, or $L_P > L_0$, in this case the rotating heads must decelerate.

In Fig. 47 and 48 both these scenarios are shown (the dotted line represents the feed of the belt conveyor). If the product length is longer than the design one, the rotating heads have to slow down in the first part of the approaching phase and then return to the (tangential) velocity equal to that of the belt conveyor before the next cutting phase in order to compensate the differences generated by a product length different from L_0 (Fig. 47).

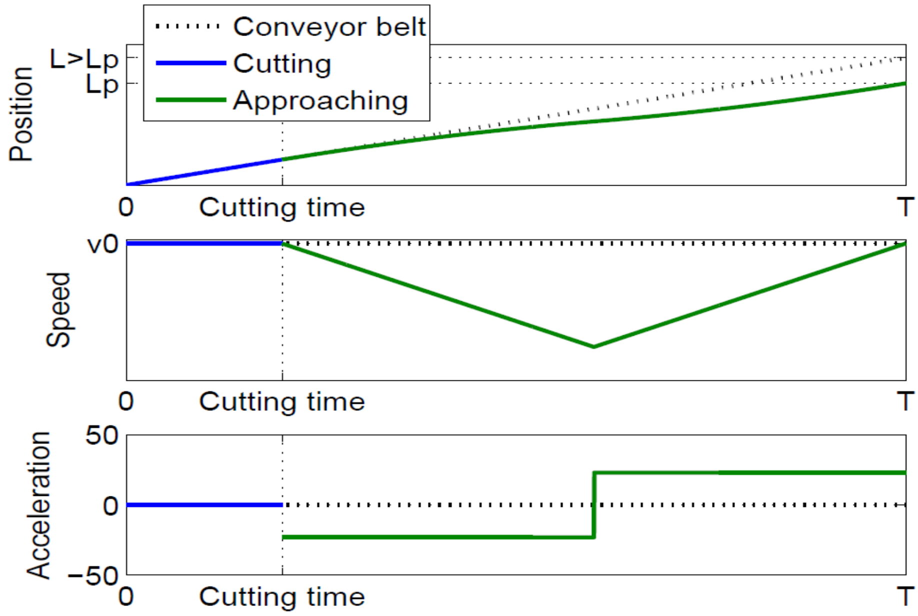

Figure 47: Motion of the rotating heads with respect to the belt conveyor ($L_P > L_0$) [12].

If the product length is smaller than L_0, the rotating heads must increase their angular speed and then return to the same speed of the conveyor belt in order to recover the length deficit (Fig. 48).

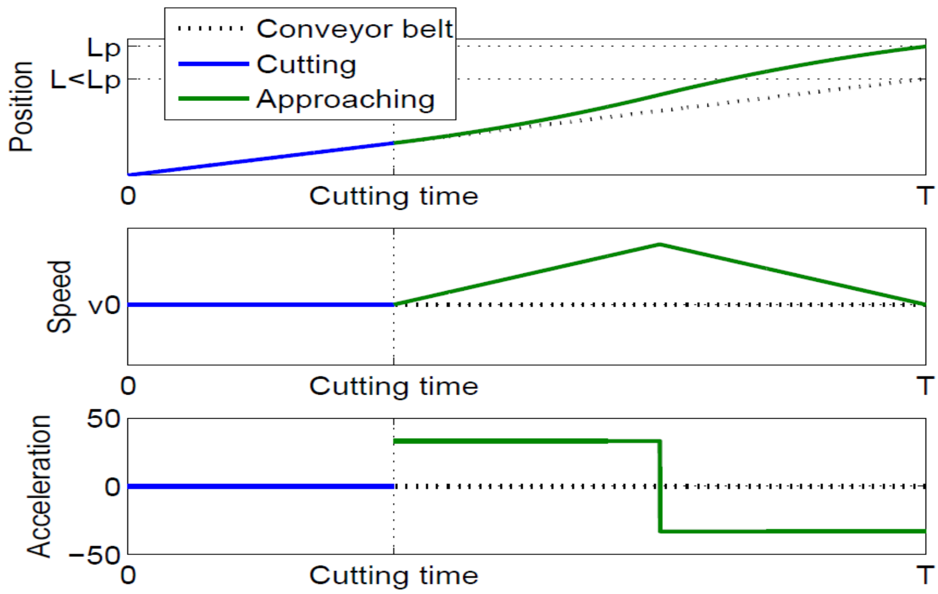

Figure 48: Motion of the rotating heads with respect to the belt conveyor ($L_P < L_0$) [12].

2.2.3 *α-β approach*

In this example the sizing of the motor-reducer unit is performed under the hypothesis of pure inertial load considering that, during the welding and cutting phases, both the friction and cutting forces are negligible; therefore, the only load that the motor have to face with is the rotating heads own inertial load.

Referring to the α-β approach described in the previous paragraph, the load factor β (Eq. 12) is directly linked to the flexibility of the machine: it is equal to zero only if $L_P = L_0$, otherwise, if the rotating heads have to accelerate or decelerate in order to process a product length greater or smaller than the L_0 it grows. Furthermore, considering the initial hypothesis, the load factor becomes

$$\beta = 4J_L \dot{\omega}^2_{L,rms} \qquad (41)$$

where J_L is the momentum of inertia of the couple of rotating heads (so $J_L(R_t) = 2J_T(R_t)$). Knowing that the dimension-less root-mean-square acceleration coefficient $C_{a,rms}$ is defined as $C_{a,rms} = \dot{\omega}_{rms} h / t_a^2$, where $\dot{\omega}_{rms}$ here is intended as the root-mean-square acceleration of the dimension-less law of motion, h is the total lift of the approaching phase and t_a is the duration period of the approaching phase, it is possible to highlight the role of the adopted law of motion on the root-mean-square value of the rotating heads angular acceleration as

$$\dot{\omega}_{L,rms} = \frac{a_{rms}}{R_t} = \frac{C_{a,rms} h T_a}{R_t T_a^2 T} \qquad (42)$$

being a_{rms} the tangential acceleration of the rotating heads, calculated on the whole duration time T while the dimension-less coefficient refers only to the approaching phase T_a. Now, considering equations (41) and (42), it is possible to express the load factor as a combination of the design terms, which are input parameters:

$$\beta = 4J_L \left[\frac{C_{a,rms} h t_a}{R_t t_a^2 T} \right]^2 = 4J_L \left[\frac{C_{a,rms}}{R_t} L_P \frac{\frac{2\pi R_t}{N} - L_P}{L_P - L_T} \left(\frac{P}{60} \right)^2 \right]^2 \qquad (43)$$

Also the range of the transmission ratio can be expressed as a function of the input parameters:

$$\Delta\tau = \sqrt{J_M} \frac{\sqrt{\alpha} \pm \sqrt{\alpha - 4J_r \dot{\omega}_{r,rms}}}{2J_r \dot{\omega}_{r,rms}} \qquad (44)$$

2.2.4 *Numerical results*

In this section some numerical results are presented referring to a wrapping machine with the parameters shown in Tab. 3:

Parameter	Value	unit
R_t	$= 0.045$	$[\mathrm{m}]$
L_T	$= 0.0236$	$[\mathrm{m}]$
P	$= 750$	$[\mathrm{pz\,min^{-1}}]$
L_0	$= 0.0942$	$[\mathrm{m}]$
J_T	$= 0.0126$	$[\mathrm{kg\,m^2}]$
$C_{a,\mathrm{rms}}$	$= 3.67$	$[-]$

Table 3: Parameters of the example wrapping machine [12].

It is important to specify that the law of motion chosen for this example is a law with symmetric trapezoidal velocity with λ = 1/3, where λ is the fraction of the time period of the law utilized respectively for accelerating, coasting at constant speed and decelerating to the starting velocity value.

In Fig. 49 the trends of β with respect to the variations both in product length and in productivity are shown: it can be seen that, as previously mentioned, if product length is equal to L_0 then β is null regardless of the productivity.

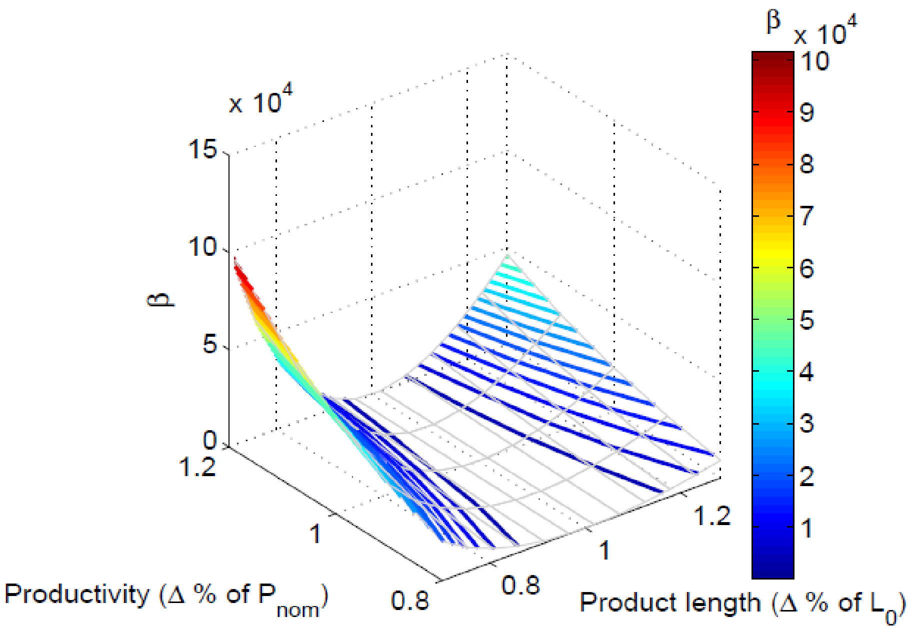

Figure 49: β as a function of product length and productivity [12].

However, considering the product length, if this parameter varies then β is not null anymore: in particular, as shown in Fig. 50, β is more sensible to a reduction then to an increase of the product length.

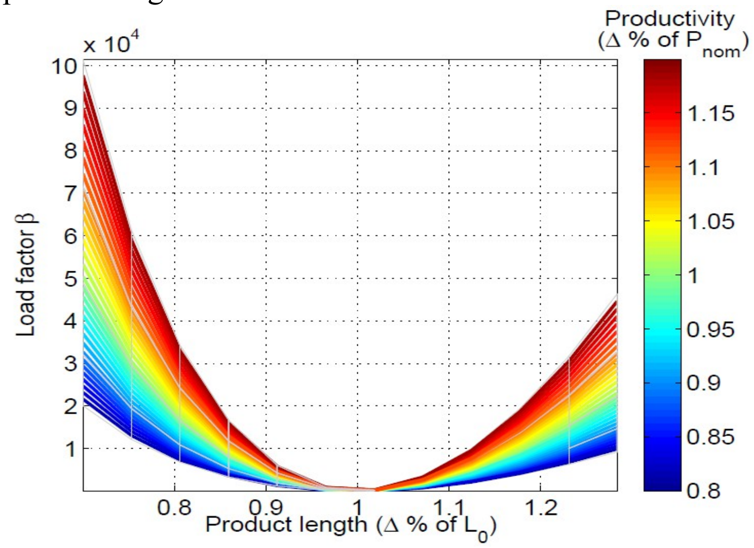

Figure 50: β as a function of product length [12].

Furthermore the load factor is more sensitive to a growth in productivity than in a change of the product length.

Besides these two parameters (product length and productivity) it is also important to consider the effect of the number of cutting tools, N, on the value of β. So, if we plot the values of the functions $\beta = f\,(L_P,\ P,\ N)$ with respect to the three input parameters, we obtain a group of surfaces, as shown in Fig. 51.

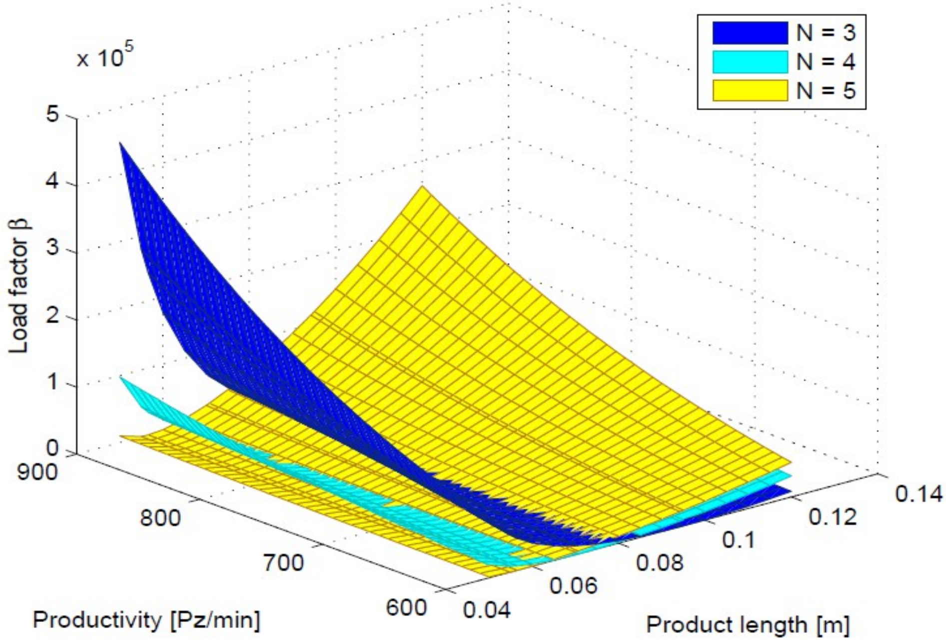

Figure 51: β with respect to $L_P,\ P,\ N$ [12].

This kind of plot can be utilized by the designer to focus on some aspects about the performance of the machine, like for example:

- the number of tools that permits, given specific product length and productivity, to package with the minimum load factor
- the number of tools that minimize the curvature of the respective surface in order to maximize the flexibility of the machine. In this example application the smoothest surface is obtained with N = 4 because if N = 3 then β grows a lot with small product length and high productivity whereas if N = 5 then β becomes a problem with high product length and high productivity
- the maximum feasible productivity with respect to some given values for the other parameters; it is important to consider that, as shown by equation (43), the load factor grows as the fourth power of P and, as a consequence, high values of β can be quickly reached.

Finally, considering a specific set of input parameters, in Fig. 52 some $\beta - \tau$ plots for four different motors are showed which depend only on the selected motor unit (α) and on the load factor (β), in order to look at the problem with a more general point of view. It is important to highlight two aspects: the first is that, the bigger the load factor becomes, the smaller the range of admissible transmission ratios $\Delta\tau$ is (in the worst case, as showed with equation (14), if $\alpha = \beta$, the only useful transmission ratio is the optimum one, τ_{opt}), the second is that this kind of plot permits to know the maximum load factor the motor can withstand.

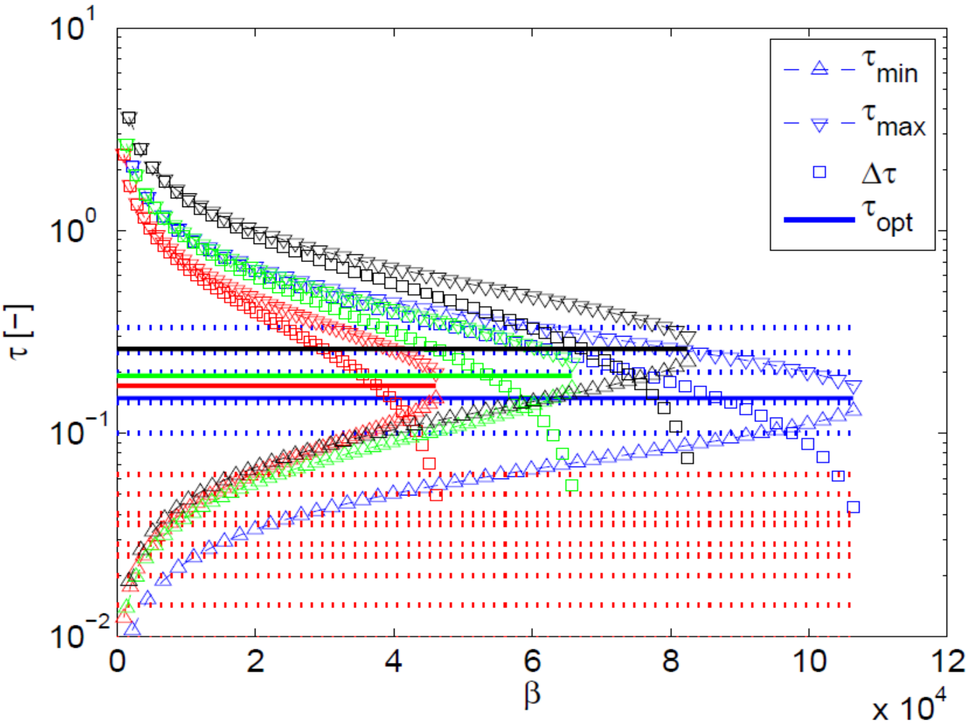

Figure 52: τ as a function of β for four different motors [12].

In conclusion, by means of the α-β method it has been possible to obtain an expression that highlights the influence of the machine parameters (such as productivity, product length, number of welding and cutting tools, motion law etc.) on the motor load factor; therefore it is possible to consider various motor-reducer solutions and to select one in order to easily optimize the performances of the machine with respect to what is required for the specific application.

2.3 Improvements to the approach

2.3.1 *Correct evaluation of η*

The method exposed in the previous paragraphs considers the mechanical efficiency (η) of the reducer as a constant value, this in general is not true. The value of η which we can read on the constructor's catalog is referred to the nominal functioning condition of the reducer and this means that only if the transmission works in a small range around its nominal condition it is correct to consider the value read on the catalog as constant [13, 14, 15].

One of the most important factors which η depends on is the torque transmitted on the load side by the reducer, in particular we can find graphs showing the trend of the efficiency value like the one in Fig. 53 (where, for the sake of example, the efficiency curve of the RV-110E gearbox by Nabtesco is showed). In this graph it is possible to see that if the reducer works in a range of output torque lower than the half value of the output nominal torque, η decreases very quickly [15, 16]. Furthermore in Figure 53 it is possible to see that η depends also on the speed of the reducer, in particular we can see that, given a specific output torque, η decreases when the speed of the reducer rises.

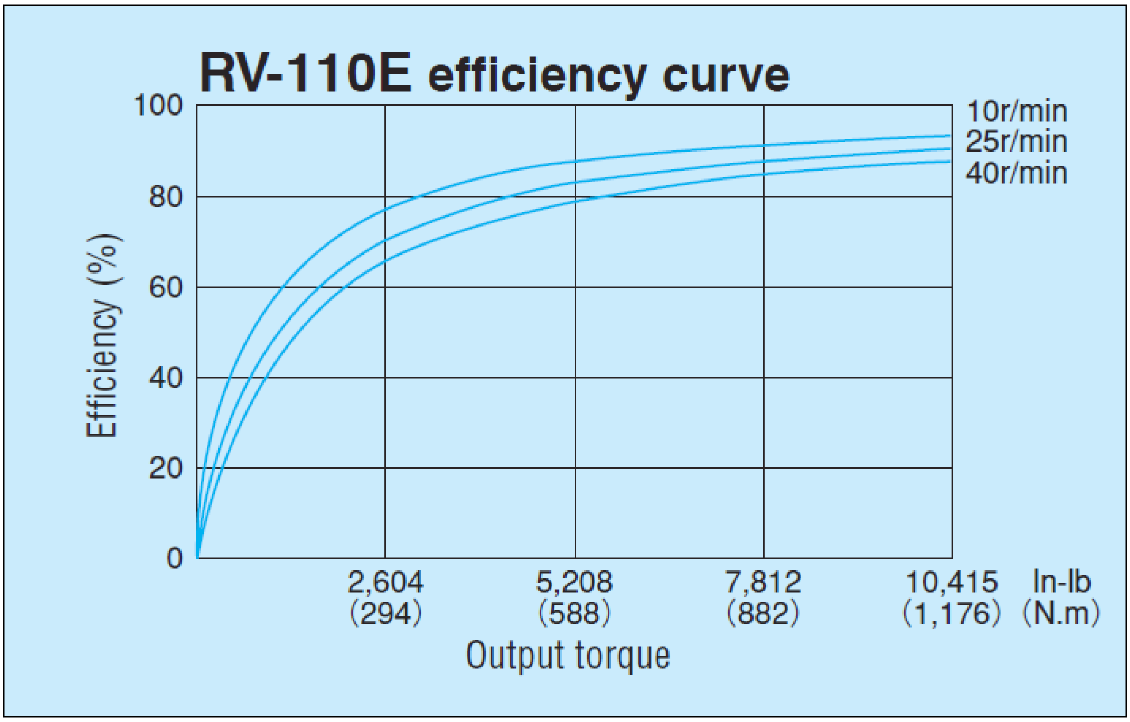

Figure 53: Dependence of η on output torque and speed of the reducer [15].

If η is lower than the value considered during the design process this means that the torque required from the motor increases and so does the power, which implies that the power loss rises. Furthermore, if the designer does not know the correct value of η, with respect to the conditions the motor-reducer couple will be working on, also the sizing of the motor will be affected and this could lead to thermal problems on the motor itself since the real working temperature of the motor will be higher than expected. This aspect is not trivial at all if the machine is working in a controlled temperature environment, which is usual in food packaging applications. So, considering how many motor-reducer couples there are in a food packaging plant, a wrong estimate of η may lead firstly to a wrong choice of the motors and secondly to an incorrect design of the cooling system of the plant.

Another important aspect of the mechanical efficiency of the reducer is that it depends on the ambient temperature too (some example curves are shown in Fig. 54).

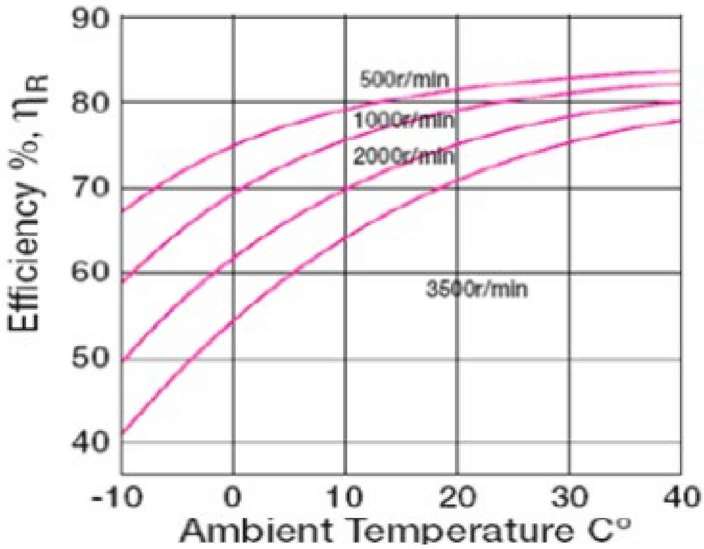

Figure 54: Dependence of η on the ambient temperature and on the speed of the reducer[15].

In Fig. 54 it can be seen that when the ambient temperature decreases, the mechanical efficiency of the reducer drops down, which, again, can be fundamental to consider when choosing the correct motors for a specific application in which the ambient temperature is low, like for example, as aforementioned, in a food packaging plant with a controlled temperature environment.

The reason why η depends on the transmitted torque, the angular speed and the ambient temperature is the friction between the various components of the transmission which generates a resistant torque: this friction, also called *no-load running torque,* is the torque that is required to rotate the gearbox without the load input (the lower the number, the higher the efficiency of the transmission) and it is almost negligible, compared to the output torque, when the reducer works around its nominal condition, but it becomes more and more relevant especially when the output torque is low, with respect to the nominal value and when the ambient temperature decreases.

In Fig. 55 the trends of the *no-load running torque* about the RV-E series gearbox by Nabtesco are presented: in particular, the graph shows the values of the no-load running torque referred to the output shaft side of the reducer, where, given τ as the value of the specific transmission ratio chosen, the relation between the no-load running torque (n.l.r.t.) referred to the input shaft side e the one referred to the output shaft side is:

$$n.l.r.t.(input\ shaft\ side) = \tau\, n.l.r.t.(output\ shaft\ side) \qquad (45)$$

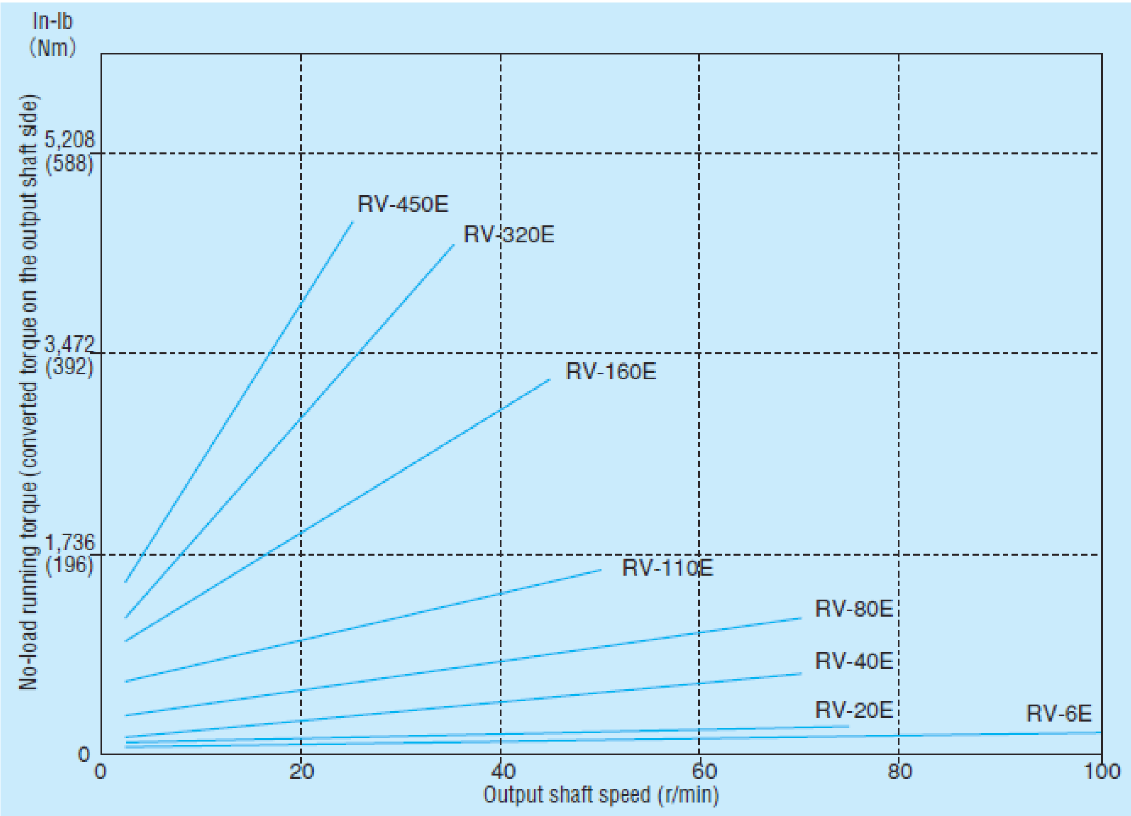

Figure 55: No-load running torque (on the output shaft side) with respect to the output shaft speed [15].

From this graph it is clear that the no load running torque consists of two components: a constant one, representative of a Coulomb friction torque, and a component, proportional to the angular speed of the reducer, which is representative of a viscous friction torque (this one in fact explains why η decreases when the speed of the transmission grows and also why η goes down in a cold environment). In particular, the value of the Coulomb component can be read on the y-axis at around zero speed, while

the value of the viscous friction coefficient can be obtained by calculating the slope of the line relative to the particular reducer considered.
Furthermore, in Fig. 56, it is represented the trend of the *no-load running torque* with respect to the case temperature value: it can be seen that when the temperature goes decreases, the *no-load running torque* increases, so explaining the trend of the gearbox efficiency shown in Fig. 54.

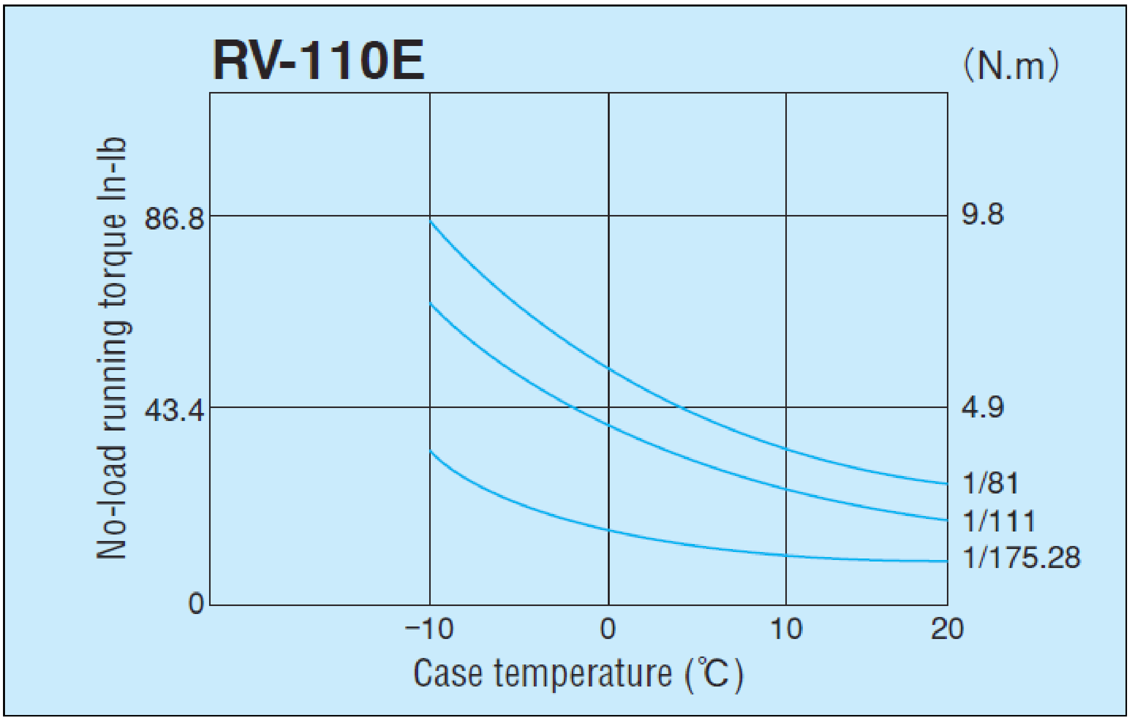

Figure 56: Trend of the *no-load running torque* with respect to the case temperature [15].

A good way to consider all these aspects about the mechanical efficiency behavior is to introduce in the model of the system (Fig. 39) two additional friction torque components: a Coulomb component which is constant, regardless of the angular speed, and equal to the *no-load running torque* for that specific reducer, and a viscous component which of course is proportional to the velocity. Furthermore, as exposed before, the value of both the constant component and the viscous coefficient may vary because of the ambient temperature so it is important to consider this aspect.

2.3.2 *Fatigue sizing*

In general, once the best τ for the specific application is chosen, η is high only if a small size reducer (compared to the pairs present) is utilized, however, if a small size reducer is chosen it is fundamental to evaluate a proper life check.

When the values of angular speed and torque that the gear unit must transmit during the operating cycle are known, then it is possible to calculate the average output torque T_m and the average output speed N_m using the formula below:

$$T_m = \sqrt[\frac{10}{3}]{\frac{t_1 \cdot N_1 \cdot T_1^{\frac{10}{3}} + t_2 \cdot N_2 \cdot T_2^{\frac{10}{3}} + \cdots t_n \cdot N_n \cdot T_n^{\frac{10}{3}}}{t_1 \cdot N_1 + t_2 \cdot N_2 + \cdots t_n \cdot N_n}}$$

$$N_m = \frac{t_1 \cdot N_1 + t_2 \cdot N_2 + \cdots + t_n \cdot N_n}{t_1 + t_2 + \cdots + t_n}$$

where T_m is measured in [Nm], N_m in [rpm] and the values N1, T1, N2, T2 etc. are defined considering the chosen law of motion, like the one in Fig. 57, as an example:

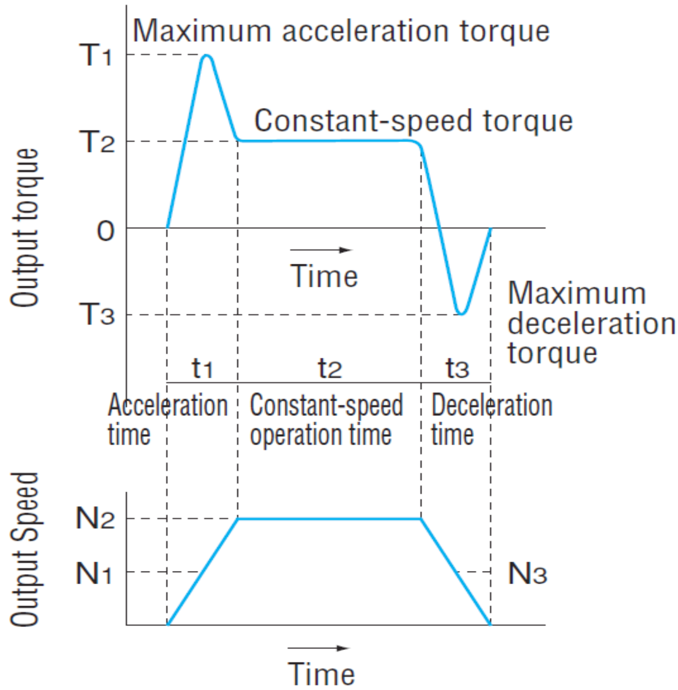

Figure 57: Duty cycle example diagram.

Once the values of T_m and N_m required by the specific application are evaluated, the designer has to select the gearbox with output torque and speed compatible with the calculated ones. The choice must verify:

$$Output\,torque \geq T_m[Nm] \quad \wedge \quad Output\,speed \geq N_m[rmp] \qquad (46)$$

When the size is selected, the service life of the gearbox L_h is calculated considering the nominal service life K and the operating conditions T_m and N_m required by the application, as derived from the DIN 69051 normative. Actual service life L_h of the reducer depends on the life of roller bearings and is estimated by the formula below:

$$L_h = K\frac{N_0}{N_m}\left(\frac{T_0}{T_m}\right)^{\frac{10}{3}} \qquad (47)$$

in which K represents the nominal service life of the gearbox: it is set to 6000 hours for all sizes and all reduction ratios, with nominal output speed N_0 and nominal output torque T_0 (Tab. 4):

Type	Rated torque(T_0) In-lb(Nm)	Rated output speed (N_0)r/min
RV-6E	514 (58)	30
RV-20E	1,479 (167)	15
RV-40E	3,649 (412)	
RV-80E	6,944 (784)	
RV-110E	9,547 (1,078)	
RV-160E	13,887 (1,568)	
RV-320E	27,774 (3,136)	
RV-450E	39,058 (4,410)	

Table 4: Nominal output speed and torque of RV-E series reducers [15].

Furthermore there exist another method to calculate the service life of the gearbox, still with respect to bearings in it and based on DIN 69051; this is exposed below.

Considering the loads applied to the output shaft, the duration, expressed in hours, of the gearbox bearings is verified. It is important to note that the *Fr* and *Fa* loads have to be intended as the only loads on the gearbox bearings. A general scheme of the loads applied on the output shaft of the reducer is presented in Fig. 58:

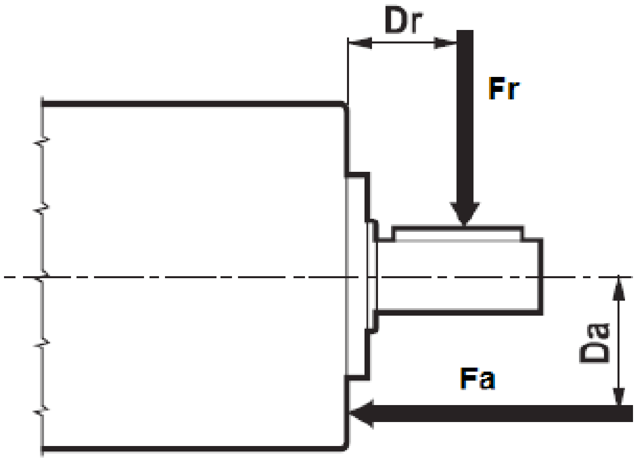

Figure 58: Schematic view of the applied loads on the reducer output shaft.

where the terms have the following meaning:

F_r = radial load on the output shaft [N];

F_a = eccentric axial load on the output shaft [N];

D_a = distance of the axial load from the reducer axis [mm];

D_r = distance of the radial load from the flange plane [mm];

First of all the maximum values must be checked:

$$F_{Rmax} > max|F_R| \quad \wedge \quad F_{Amax} > max|F_A| \qquad (48)$$

The second step is to verify the service life, expressed in hours, of the gearbox (L_{10}) with a survival chance of 90%.

With reference to a generic mechanical system, it is possible to model the reliability behavior claiming that the product between the applied load F_{eq}, elevated to an exponent (usually 3), and the life, expressed in number of rotations L_{rot}, is constant for a family of identical components: $F_{eq}^3 L_{rot} = F_{eq}^3 60 n\ L_h = constant$ (where L_h is the life expressed in hours, n is the speed expressed in rpm).

By comparing the operating conditions of the application (n_{2mean}, F_{eq}) with the nominal conditions this leads to the following equation:

$$L_{10} = \frac{b}{n_{2\text{mean}}}\left(\frac{C}{F_{eq}}\right)^3 \quad [h] \qquad (49)$$

where:

b = characteristic parameter of the gearbox, expressed in [h*rpm], representative of the life test mode carried out by the manufacturer (usually 16666 h*rpm);

C = characteristic parameter of the gearbox, expressed in [N] or [Nm], representative of the load used in the life test by the manufacturer;

F_{eq} = equivalent mean force (torque), result of axial and radial forces, expressed in [N or Nm]: $F_{eq} = F_{am} D_a + F_{rm}(D_r + d_r)$, where d_r is a calculation constant, characteristic of the reducer, while F_{am} and F_{rm} are the axial and radial mean forces in the cycle respectively and they are defined as follows:

$$F_{am} = \sqrt[3]{\frac{\left|t_a n_{2a} F_{a\_a}^3\right| + \left|t_k n_{2k} F_{a\_k}^3\right| + \left|t_d n_{2d} F_{a\_d}^3\right|}{t_a n_{2a} + t_k n_{2k} + t_d n_{2d}}} \quad F_{rm} = \sqrt[3]{\frac{\left|t_a n_{2a} F_{r\_a}^3\right| + \left|t_k n_{2k} F_{r\_k}^3\right| + \left|t_d n_{2d} F_{r\_d}^3\right|}{t_a n_{2a} + t_k n_{2k} + t_d n_{2d}}}$$

in which subscripts (*_a, _k, _d*) refer to the three stages of acceleration, constant speed and deceleration.

Standard gearboxes are generally equipped with bearings suitable for working in conditions where $F_{am} / F_{rm} < 0.2$. Otherwise particular realizations, with suitable special bearings, are required.

Obviously, for the calculation of the actual service life to be correct it is necessary to provide the correct lubrication for the gearbox. The specifications for lubrication are given in the manufacturers' catalogs. As an example, in the Nabtesco catalog, it is specified that the RV-E series gearboxes are supplied without lubricant inside, which must therefore be added before putting the reducer into service; specifically, Nabtesco uses a grease lubrication in order to avoid leakage (which are more likely to occur in the case of oil lubrication). Nabtesco also specifies the temperature range within which the standard lubrication is sufficient (-10 / +40 °C) and the amount of grease to be added in the gearbox according to the model and the orientation in which it is mounted (horizontal or vertical) through the following tables.

Horizontal installation

Type	Quantity cc	(g)
RV-6E	42	(37)
RV-20E	87	(76)
RV-40E	195	(170)
RV-80E (Bolt clamping)	383	(333)
RV-80E (Pin/bolt clamping)	345	(300)
RV-110E	432	(376)
RV-160E	630	(548)
RV-320E	1,040	(905)
RV-450E	1,596	(1,389)

Table 5: Grease quantity in RV-E reducers installed in horizontal configuration [15].

Vertical installation

Type	Quantity cc	(g)
RV-6E	48	(42)
RV-20E	100	(87)
RV-40E	224	(178)
RV-80E (Bolt clamping)	439	(382)
RV-80E (Pin/bolt clamping)	396	(345)
RV-110E	495	(431)
RV-160E	694	(604)
RV-320E	1,193	(1,038)
RV-450E	1,831	(1,593)

Table 6: Grease quantity in RV-E reducers installed in vertical configuration [15].

Finally it is recommended to change grease at a standard interval of 20,000 hours after initially supplying the RV-E reduction gear with grease in the specified quantity (Tab. 5 - 6) in order to protect the RV-E reduction gear from deteriorated grease.

2.3.3 M*odification to the Step 7 of the aforementioned approach*

In general η (and equivalently both the components of the *no-load running torque*) depends on the size of the reducer; in the method exposed in the previous paragraphs the choice of the specific transmission is done in the final steps and only in step 7 the

mechanical efficiency is considered, together with the moment of inertia. At this point the gearbox is chosen and so it becomes possible for the designer to know the proper values of the *no-load running torque* components by reading them on the constructor's catalog or by asking the constructor if they are not indicated.
It is important to point out that the method exposed in the previous paragraphs is very immediate because β is defined as dependent only on the load; so, in order to maintain this characteristic, and considering that the Coulomb's friction torque component and the viscous one are normally referred to the motor side of the gearbox, these two friction torque components that evaluate the effect of the transmission's mechanical efficiency have to be considered only in the last step, when the transmission is already chosen and only the last checks have to be done. Furthermore, an advantage of adding these two friction torques at the end of the procedure is that, if the values needed (the *no-load running torque* and the viscous coefficient) are not present in the catalog, the designer will have to ask the constructor only for the values relative to the specific reducer chosen.
Finally, to summarize this addition to the procedure of the first paragraph it is possible to modify the inequalities in *Step 7* as follows.
Equation (25) becomes

$$T_M - (C_{coulomb} + f_{viscous}\,\omega_M) = (J_M + J_T)\dot{\omega}_M + \tau T_L^{+} = (J_M + J_T)\frac{\dot{\omega}_L}{\tau} + \tau T_L^{+} \quad (50)$$

which means that

$$T_M = (J_M + J_T)\frac{\dot{\omega}_L}{\tau} + \tau T_L^{+} + \left(C_{coulomb} + f_{viscous}\frac{\omega_L}{\tau}\right) \quad (51)$$

So, regarding *Step 7*, inequality (26) becomes

$$T_{M,max}(\omega_M) \geq max\left|(J_M + J_T)\frac{\dot{\omega}_L}{\tau} + \tau T_L^{+} + \left(C_{coulomb} + f_{viscous}\frac{\omega_L}{\tau}\right)\right| \quad (52)$$

and inequality (27) becomes

$$T_{M,N}^2 \geq T_{M,rms}^2 = \int_0^{t_a} \frac{T_M^2}{t_a} dt = \int_0^{t_a} \frac{1}{t_a}\left[(J_M + J_T)\frac{\dot{\omega}_L}{\tau} + \tau T_L^{+} + \left(C_{coulomb} + f_{viscous}\frac{\omega_L}{\tau}\right)\right]^2 dt \quad (53)$$

It is important to note that in equations (50) to (53) the mechanical efficiency does not appear anymore because its contribute is already considered by means of the two additional friction torque components which is, as explained before, a more precise method to evaluate the non constant efficiency of the gearbox; anyway, if for example the viscous coefficient is not given by the constructor, it is better to consider both the Coulomb's friction torque and the mechanical efficiency in order to be sure to have a sufficient margin about the motor characteristics.

Finally, for the selected reducer, it must be verified that the service life L_h, defined according to the conditions of use T_m and N_m, is equal to or higher than the service life $L_{hproject}$ required by the application:

$$L_h \geq L_{hproject} \qquad (54)$$

In case the service life L_h is lower than the service life required $L_{hproject}$, the designer should choose the immediately larger available size for the reducer and repeat the checks.

CHAPTER 3

THE WELDING PROCESS: A COMPARISON BETWEEN CONDUCTION AND ULTRASONIC SEALING

The aim of this chapter is to focus on the welding process, which is a fundamental phase of food packaging. In particular two of the most important heat sealing techniques will be analyzed: conductance and ultrasonic sealing. After an introduction about the heat welding process [17, 18], in the second paragraph a focus on the conduction sealing is proposed [17, 18, 19, 20] whereas in the third paragraph the ultrasonic sealing technique is analyzed [18, 19, 21, 22, 23, 24, 25]. In the fourth paragraph a comparison between the two techniques is presented together with some experimental results [22]. Finally, in the last paragraph some conclusive considerations about the two analyzed welding techniques are exposed [23, 24, 25].

3.1 Introduction

Heat sealing involves welding thermoplastic polymer surfaces together in order to produce joints of sufficient strength to withstand stresses in the distribution and consumer environment.

The realization of the joints is a critical step in food packaging mainly for two reasons. The first is the time required for welds as it affects productivity. In flow pack machines, both vertical and horizontal, used in the food packaging industry, two types of welds can be distinguished in each package, the transverse and the longitudinal ones (Figures 59*a* and 59*b* respectively): the time intervals in which they are made depend on the wrapping material characteristics and the specific welding technique used.

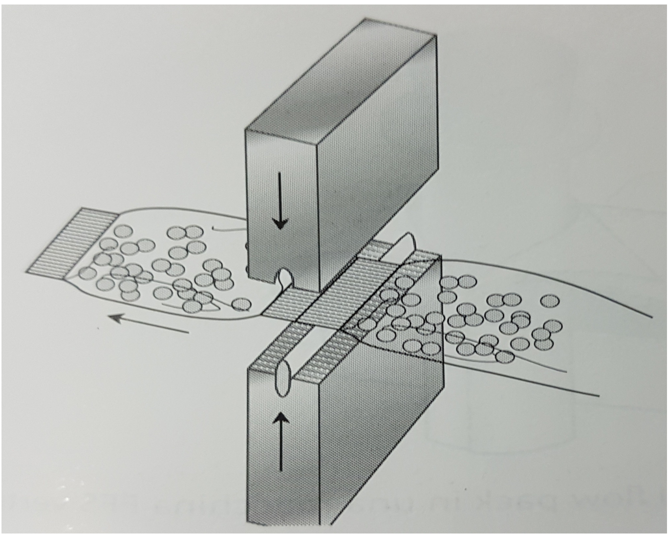

Figure 59*a*: Schematic of transverse sealing in an horizontal wrapping machine [17].

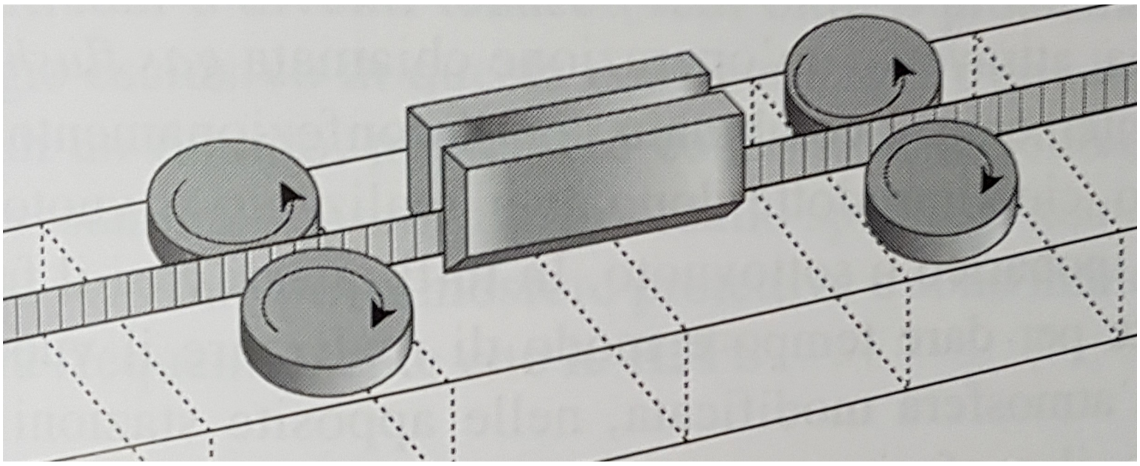

Figure 59*b*: Schematic of longitudinal sealing in an horizontal wrapping machine [17].

The second reason is the possibility of influencing the product's shelf life, that is the length of time that a product may be stored without becoming unfit for consumption: a poorly welded package or even a package with a discontinuous welding (a seal which presents microleakages) can result in air entering or, in the case of map packaging, in some specific protective atmospheres escaping.

Furthermore it is worth noting that the most critical points of a sealing are the corners of the packages, the crossing points between longitudinal and transverse welds and the overlapping of the layers, as showed in Fig. 60.

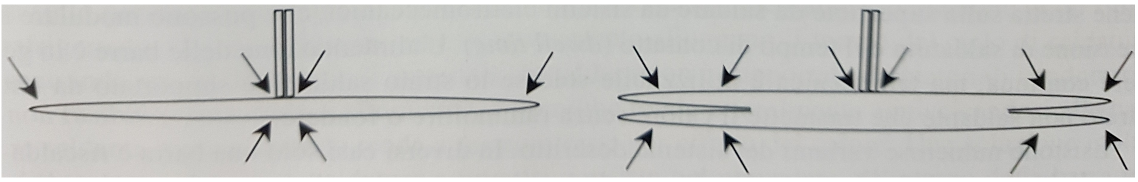

Figure 60: Schematic view of critical welding points for packages with and without gussets [17].

In these points, overlapping of several layers hampers heat transmission and folding of the material into the angles causes the welding to be subjected to further tensions; all this is emphasized more with some materials than with others. An example is paper-based packaging materials (e.g. Rana's tortellini): they usually consist of three layers (paper, nylon, polyethylene) reaching a thickness of about 80 μm; in the case of gussetted packages, there are two thicknesses (160 μm) to four (320 μm). Low thermal conductivity and low paper compressibility make welding difficult; in the case of a conductance sealing system (see the next paragraph) the fundamental variables are pressure, temperature and welding time, and because of the fact that with the paper-based materials the jaws temperature is already close to the maximum limit (about 210-215 °C) in order to cope with the low thermal conductivity of the paper layer, this implies that, with this type of material, to keep the welding time low (and therefore maintain an high machine productivity) it is essential that the welding system guarantees a large pressure between the jaws.
Heat sealable films are considered those films that can be bonded together by the normal application of heat; in this context temperature plays a fundamental role. As can be seen in Fig. 61, where the general trend of breaking strength vs welding temperature is showed, regardless of the specific values which change with different materials, the breaking strength for welds made at low temperatures is reduced; it reaches the maximum at the optimum temperature, which is typically some degree above the melting temperature and ensures maximum interaction between the layers of the two edges of material; further increasing the temperature, the toughness decreases because of the greater mobility of welding layers that are thinned in the sealing zone.

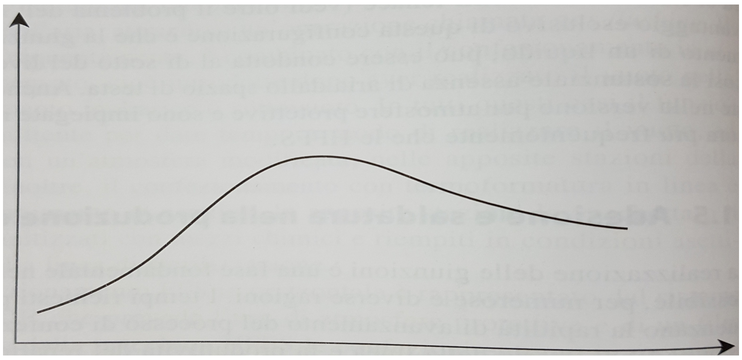

Figure 61: The x-axis represents the welding temperature and the y-axis represents the breaking strength of welds (measured in N cm^{-1} after the cooling phase) [17].

Finally there are two types of seals (Fig. 62). A *fin* seal (image *a*) is formed when the inside surface of the film is welded against itself: it is commonly used to form the top and bottom seals on horizontal or vertical wrapping machines. A *lap* seal (image b) is formed when the inside surface of the film is welded against the outside surface of the film: it is commonly used to form the longitudinal (back) seal on vertical wrapping machines.

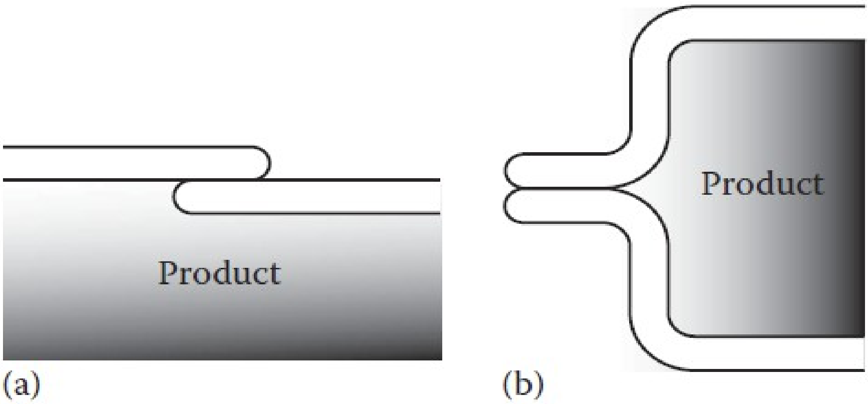

Figure 62: Different types of seals: *fin* seal (image *a*), *lap* seal (image b) [18].

3.2 Conductance sealing

Conductance (also known as resistance or bar) sealing systems, Fig. 63, are certainly the most utilized in the food packaging industry and typically consist of two metal jaws or bars (often serrated to give the seals extra strength), one of which is electrically heated, the temperature being controlled thermostatically, via an electrical resistance. The second, or backing, jaw is often covered with a resilient material such as rubber to distribute pressure evenly and aid in smoothing out the film in the sealing area. Frequently the unheated jaw is water cooled although in some situations it may be heated to the same temperature of the first jaw in order to reduce the welding time and enable sealing through sheets of film in exactly the same way. The edges of the jaws are often rounded to avoid puncturing the packaging material.

Serrated jaws can be used to ensure that the two webs are stretched into intimate contact with high local pressure; they improve appearance too. Furthermore, as shown in Fig.64, the knurled bars can have very different profiles and the choice is neither casual nor irrelevant to the effectiveness of welding.

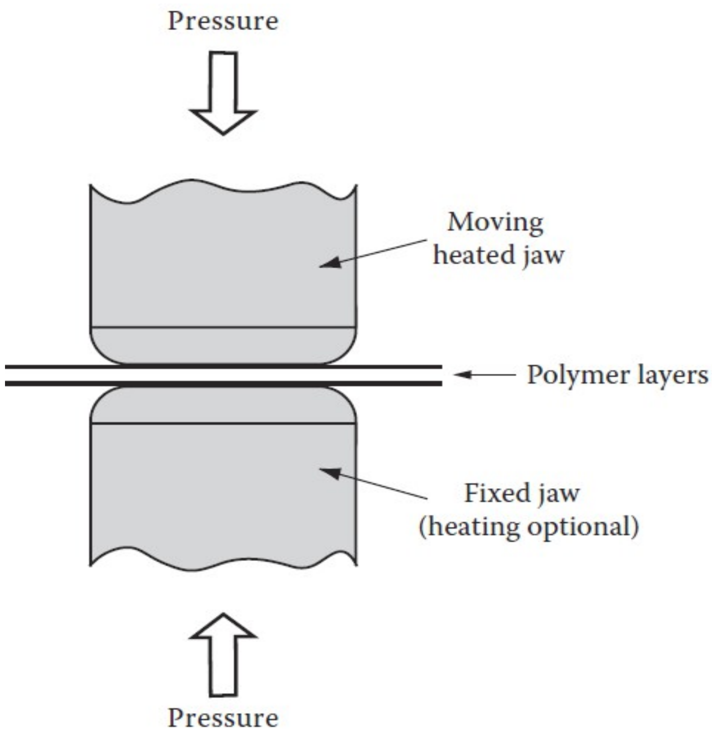

Figure 63: Schematic view of a bar sealing system [18].

Vertical knurl gives greater welding toughness but is more frequently subject to the formation of microchannels that affect the quality of the seal; this defect is much less likely with horizontal knurl, which, however, provides less robust welds. For all sealing jaws, a nonstick coating is desirable: PTFE is commonly used.

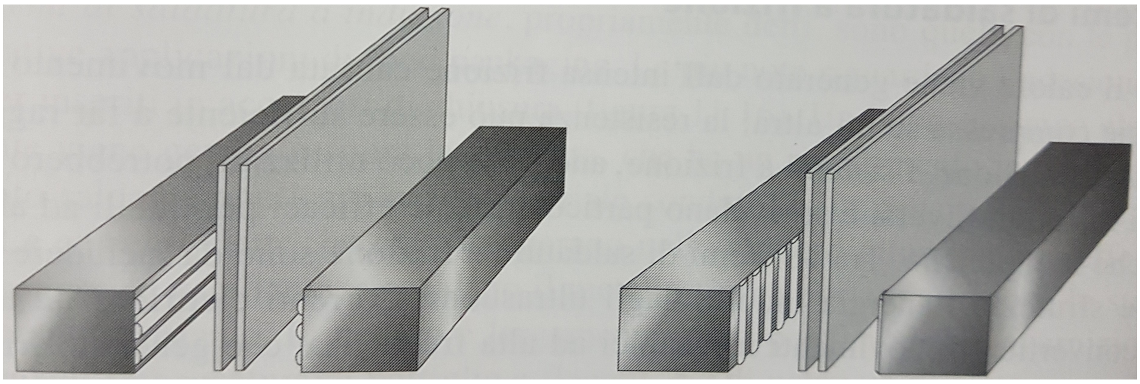

Figure 64: Serrated sealing jaws with horizontal knurl (left image) and vertical knurl (right image) [17].

The welding parameters important to this process, as anticipated in the introduction of the chapter, are bar temperature, weld pressure and weld time. Hot-bar welding can be a rapid process and its typical welding times can be less than one second.

Dwell time should be able to be controlled to fractions of a second and easily adjustable as it needs to be changed when different materials are heat sealed. Likewise, the pressure between the jaws should be easily adjustable too: this parameter in fact permits to improve the “quality” of the contact between the layers of the film between the jaws and this in turn improves the heat exchange between the jaws and the film. The result is that it can be possible to reduce the welding time, given a specific temperature of the jaws, by increasing the welding pressure. This fact is very important and it is not trivial at all considering that for many years the manufacturers of packaging machines have overlooked the welding pressure.

In general, welding pressure becomes more and more important when using "difficult" welding materials. In food packaging the most used adhesive is polyethylene, which melts at about 125 °C, but there are other layers of film between the hot bar and the polyethylene, so for adhesive to reach 125 °C the hot bar should be set at a higher temperature and the temperature delta depends on the specific material of which the other layers of the film to be welded are made up. In general, nylon has a good thermal conductivity (0.38), therefore, with welding bars at around 145-150 °C, it is possible to obtain thermal flow sufficient to bring the polyethylene to 125 °C in a short time; however there are materials such as polypropylene or polyester having lower thermal conductivity. Finally, the worst material is paper, which has a thermal conductivity between 0.12 and 0.25 and therefore requires higher jaw temperatures for polyethylene to melt.

As known by the Fourier formula (Eq. 55) that regulates stationary (i.e. constant in time) heat conduction phenomena, the heat exchanged between two surfaces at different temperatures also depends on the time interval during which the two thermal sources stay in contact:

$$\dot{Q} = -\lambda \; A \frac{dT}{dx} \qquad (55)$$

where $\dot{Q}$ represents the heat transferred per unit of time, λ is the thermal conductivity, A is the area of the surface, dx is the infinitesimal thickness and dT is the infinitesimal temperature difference

In general, when using films with low thermal conductivity layers, because of the fact that it is not possible to increase the temperature of the jaws beyond a certain limit value due to the risk of spoiling the film, it is often necessary to use long welding times (e.g. 500 ms), which for horizontal or vertical wrapping machines are very long times (they are acceptable instead in pouch machines where the goal is to make the "perfect" bag, as seen in the first chapter) and imply a remarkable reduction in productivity compared to the products made with easier to weld films. To solve the problem of high welding time when using films that are difficult to seal it is therefore extremely useful to impose a very high pressure between the jaws and the film, thereby improving the contact between the materials and so the thermal exchange: this allows to get the polyethylene layer to 125 °C in less time.

With conventional hot-bar welding, the heated bar is removed while the weld is still molten, therefore the joint is not under pressure during the cooling phase. This can sometimes lead to reopening of the weld after the bars are released, especially if the films are under tension. In an attempt to solve this problem, a new variant of hot-bar welding, called heated tool/cooled tool welding, has been developed where pressure is applied with the aid of a cooled tool, which replaces the heated tool after the heating cycle has elapsed.

A variation on this type of sealer is the band sealer, where the films travel between two endless bands of metal that are pressed together by heated bars (Fig. 65). The heat passes through the bands and seals the films; the bands are then pressed together by chilled bars to withdraw heat from the seal. Band sealers are widely used for sealing pouches and have the advantage of being continuous.

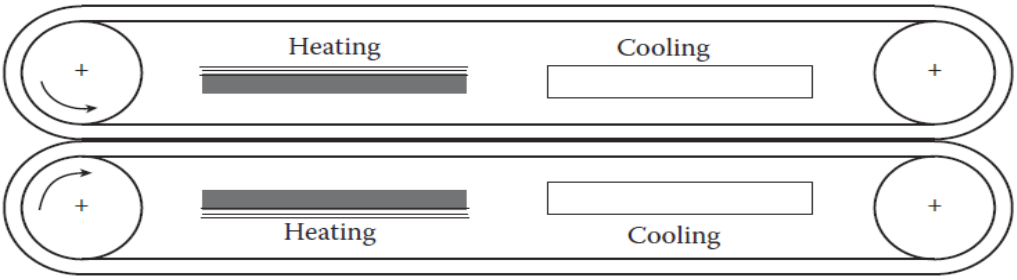

Figure 65: Schematic view of a band sealer [18].

Finally, another possible configuration of a conductance sealing system consists of pairs of welding wheels which are often used in horizontal FFS machines for the longitudinal seals (Fig. 66).

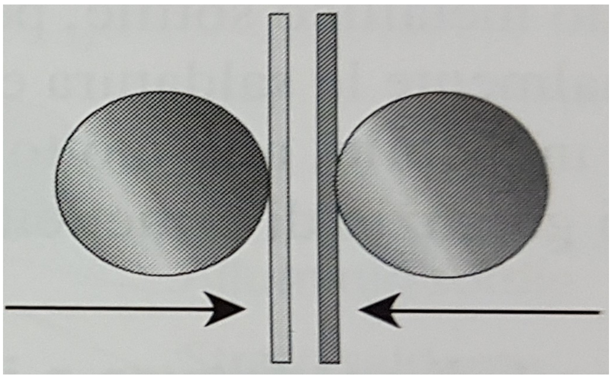

Figure 66: Schematic view of a pair of welding wheels [17].

A very important aspect is the material with which welding bars are made, in this regard there are several possibilities, such as aluminum, stainless steel, copper and nickel alloys, simple steel.
Aluminum has good thermal conductivity (≈ 220 W/m°C), low specific weight (≈ 2.7 Kg/dm^3) and therefore low thermal capacity. This means that the aluminum jaws have excellent thermal uniformity throughout the surface (which also makes the temperature control system, based on the measurements of a sensor located on the bars, more effective as these measurements will be more correct) and are able to exchange heat

very quickly. Generally, this latter aspect is an advantage in machine start-up phases as it takes little time to bring the welding bars to the correct temperature, which means an increase in productivity, however, it can lead to disadvantages in particular sectors such as the dairy industry, where, in case of water spills when bags are being closed, the temperature of the jaws can drop rapidly, compromising the welding of the subsequent bags.

Aluminum welding bars are usually also provided with surface treatments such as Excalibur or Durit (registered trademarks) in order to improve the characteristics of the material: the first is a particular shallow teflon coating that has low surface hardness and therefore the bars have to work in clean environments as they can not be brushed, the second one has a higher hardness (about 800 Vickers), so it is brushable, but with the temperature changes of the welding bars it cracks (Fig. 67).

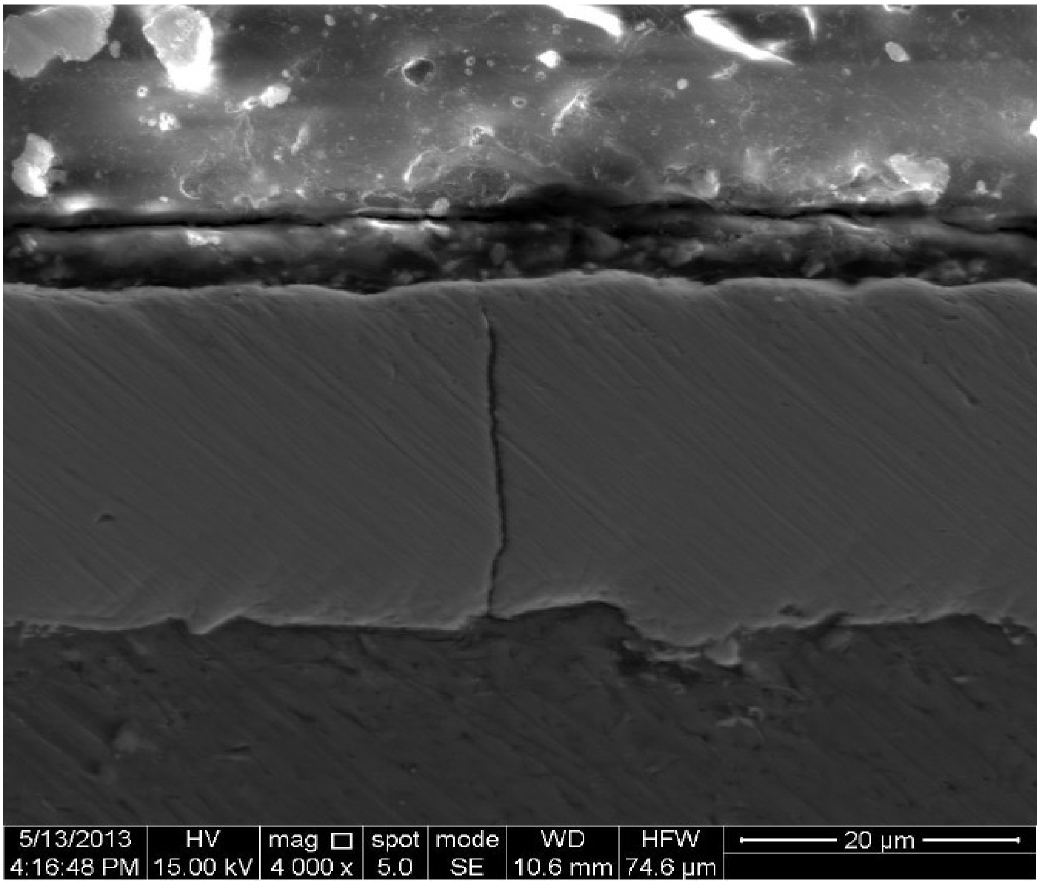

Figure 67: Fracture in an aluminum welding bar with Durit coating [20].

Aluminum welding bars are therefore indicated in the case of welds to be carried out in clean environments, e.g. in pouch machines, where they are used to make welds on the three sides of the bag, i.e. in stages prior to product insertion.
Another chance would be to make stainless steel welding bars so that they have a brushable and anti-rust material and therefore they would be optimal for environments where jaws have to be frequently cleaned. However, the stainless steel has an extremely low thermal conductivity (≈ 12 W/m°C): this results in a considerable uneven temperature distribution on the surface of the welding bar, and it is also necessary a long time to exchange heat. The latter aspect therefore implies very long machine start-up times, at the expense of overall productivity.
A solution which goes in between the two aforementioned is the use of C40 steel welding bars, which has a better thermal conductivity (≈ 40 W/m°C) than stainless steel: the jaws are fast enough to heat in machine start-ups but at the same time not too fast to cool if they become dirty due to a leak of the product from the bag. The problem of rust is still present therefore the jaws have to be brushed frequently and occasionally replaced.
Finally, it is possible to use jaws made of alloys mainly composed of copper (about 90%) and nickel (about 7%) that have a thermal conductivity similar to that of aluminum together with a high mass (specific weight ≈ 8.5 Kg/dm^3) and therefore they have an high thermal capacity. In this case, therefore, welding bars are obtained which do not cool down quickly and at the same time guarantee a uniform temperature throughout the surface. With this type of alloys the problem of rust is still present so, considering the higher cost with respect to the C40 steel, it is better to use these jaws in clean environments.

3.3 Ultrasonic sealing

3.3.1 *Process description*

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) machines that utilize the ultrasonic sealing method. This method of welding plastic parts has short welding times compared with conduction sealing. During ultrasonic welding, the polymer parts or films get compressed and oscillated by vertical vibrations via a specific tool, called “horn”. An 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 range from 20 to 40 kHz. The amplitude of the converter is transformed by a mechanical booster. Finally, as written before, the oscillation is transformed and transferred to the welding parts or films by the horn (Fig. 68).

In order 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 in turn 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. The heat-sealing jaws and the resulting seams are instead often wider than ultrasonically sealed seams and they are also often shaped or rifled to improve the seam quality.

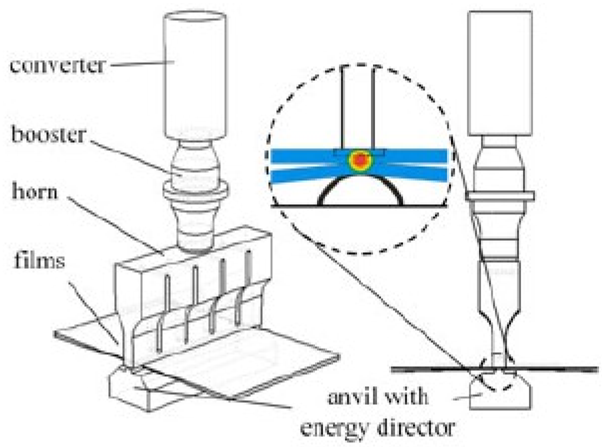

Figure 68: Configuration for ultrasonic sealing systems [22].

In the 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: some manufacturers (e.g. Mondelez and Nestlé) are beginning to ask for systems that allow to overlay ultrasonic welding with a conduction sealing in order to improve the aesthetic performance of the overall welding.

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 horn and the anvil being a lot cooler. The resulting temperature profiles for both methods are schematically illustrated in Fig. 69 where the different curves represent different points in time (proceeding sealing time).

In the process cycle for a non-continuous conduction 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. Furthermore, the horn has to be charged with force to ensure the transmission of the vibration to the films.

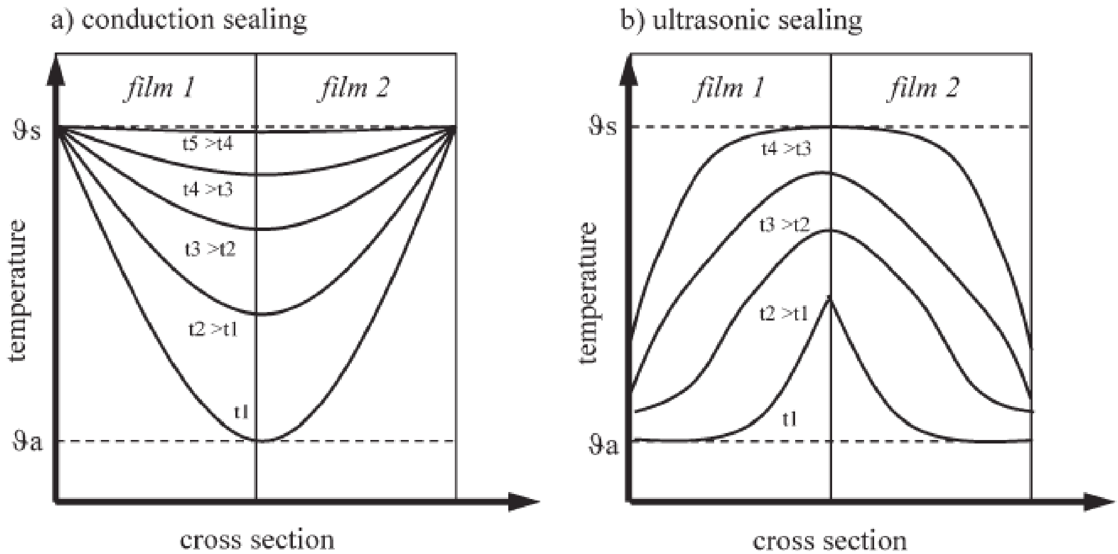

Figure 69: Temperature profiles in the cross section of the fusion zone for increasing sealing time (t) for conduction sealing (a) and ultrasonic sealing (b) [22].

In ultrasonic sealing the heat generation is stopped by switching off the ultrasound, the seam may then be able to cool down in contact with the cold 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 cold tools prevent melting of the product during downtimes, which helps to reduce rejections. In this context, the ultrasonic sealing method may help to reduce costs for packaging materials.

3.3.2 *Equipment*

Equipment for ultrasonic welding consists of a power supply, a converter with booster attachment to increase or decrease the amplitude of vibration, a horn, an anvil to support the parts being welded and to properly direct the energy, and a pneumatic welding press that contains the converter, booster, horn, and pneumatic controls.

The power supply, also called “generator” converts the 50 – 60 Hz line voltage into a high voltage signal at the desired frequency (typically 20 to 40 kHz).

Power supplies are available with varying levels of process control, from basic to microprocessor-controlled units; power output ranges up to 8000 W (in the case of continuous applications). Controllers can operate at a constant frequency or, in newer models, the amplitude can be changed instantaneously during welding, in either a stepwise or a profile mode.

The transducer, also known as “converter”, is the key component of the ultrasonic welding system. The transducer converts the electrical energy from the generator to the mechanical vibrations used for the welding process. A schematic of the component is shown in Fig. 70.

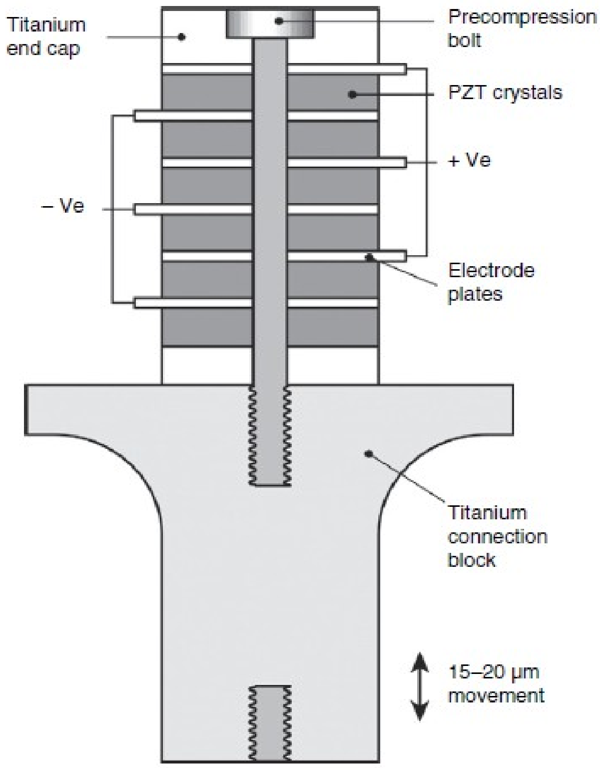

Figure 70: Schematic view of an ultrasonic transducer [19].

The transducer consists of a number of piezoelectric ceramic (lead zirconate titanate, PZT) discs sandwiched between two metal blocks, usually titanium. Between each of the discs there is a thin metal plate, which forms the electrode. As the sinusoidal electrical signal is fed to the transducer via the electrodes, the discs expand and contract. The most common frequencies of vibration used in ultrasonic welding are from 20 to 40 kHz. The amplitude, or peak-to-peak amplitude, is the distance the converter moves back and forth during mechanical vibrations. Typical values are 20 μm for a 20 kHz converter and 9 μm for a 40 kHz converter.

Since the piezoelectric discs have poor mechanical properties in tension, a bolt through the center of the device is used to precompress the discs. This ensures that the discs remain compressed as they expand and contract.

Depending on production environment conditions, ultrasonic converters are usually available with protection ratings of IP50, IP65 and IP67. In Fig. 71 an image of some actual transducers.

Figure 71: Ultrasonic converters change electrical oscillation to mechanical vibrations[23].

The booster is a component mounted between the converter and the horn to couple the ultrasonic vibrations from the converter to the horn. The primary purpose of the booster is to amplify the mechanical vibrations produced at the tip of the transducer. The secondary purpose is to provide a mounting point to attach the welding stack (transducer/booster/horn) to the actuator.

Boosters that change the amplitude are machined with different masses on either side of the booster's center or 'nodal' point (Fig. 72).

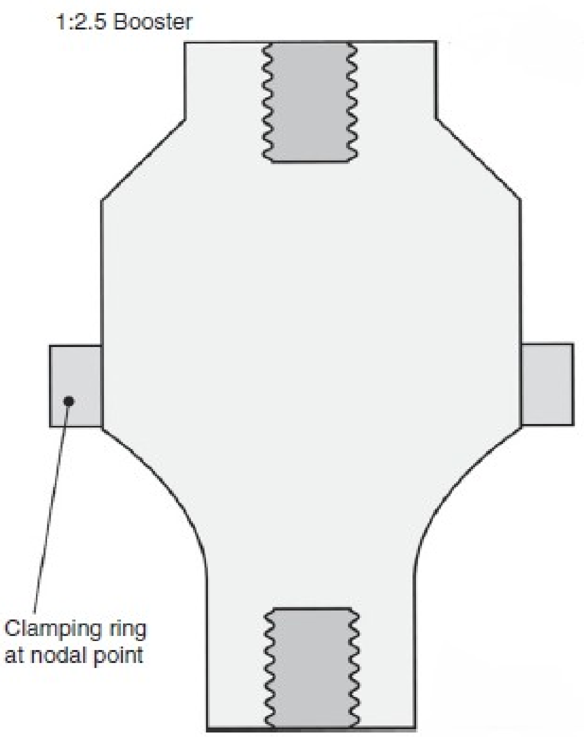

Figure 72: Schematic view of a 1:2.5 booster [19].

The amplitude is increased when the lower-mass end is attached to the horn; conversely, the amplitude is decreased when the lower-mass end is attached to the converter. The magnitude of increase/decrease is proportional to the mass differences, expressed as a gain ratio. The gain ratios are usually marked on the booster or indicated by color coding (Fig. 73).

A metal ring around the center (nodal point) acts as the clamping point to the actuator, where the load can be transferred from the welding press to the components being welded.

Figure 73: Example of titanium ultrasonic boosters [23].

A welding horn, also known as a sonotrode, is an acoustical tool that transfers the mechanical vibrations to the workpiece, and is custom-made to suit the requirements of the application. The molecules of a horn expand and contract longitudinally along its length, so the horn expands and contracts at the frequency of vibration. Horns are designed as long resonant bars, the amplitude of the horn is determined by the movement from the longest value to the shortest value of the horn face in contact with the part (i.e. peak-to-peak movement). By changing the cross sectional shape of a horn, it is possible to give it a gain factor, increasing the amplitude of the vibration it receives from the transducer – booster combination. Three common horn designs are the step, exponential, and catenoidal, as shown in Fig. 74-76.

The optimum oscillation behavior of the ultrasonic sonotrodes is determined by means of FEM (Finite Element Method) calculation. Highest precision requirements in terms of CAD calculation algorithms guarantee precise 3D contours for sonotrode manufacturing. Measuring and documentation of the amplitude distribution is performed at the vibrating sonotrode using laser measurement technology.

Step horns (Fig. 74) consist of two sections with different but uniform cross-sectional areas; due to the abrupt change in the cross-section, step horns have a very high stress concentration in this area and can fail if driven at excessive amplitude. Gain factors up to 9:1 can be attained with this type of horns.

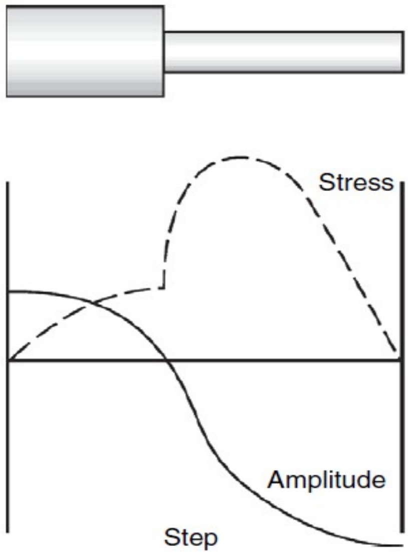

Figure 74: Step horn profile [19].

Exponential horns (Fig. 75) have a cross-sectional area that changes exponentially with length. The smooth transition distributes the stress over a greater length, thus offering lower stress concentrations than that found in step horns. They generally have lower gain factors, so are used for applications requiring low forces and low amplitudes.

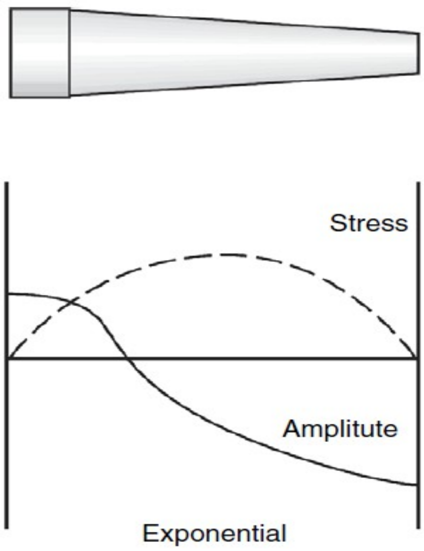

Figure 75: Exponential horn profile [19].

Catenoidal horns (Fig. 76) are basically step horns with a more gradual transition radius through the cross section. They offer high gains with low stress concentrations.

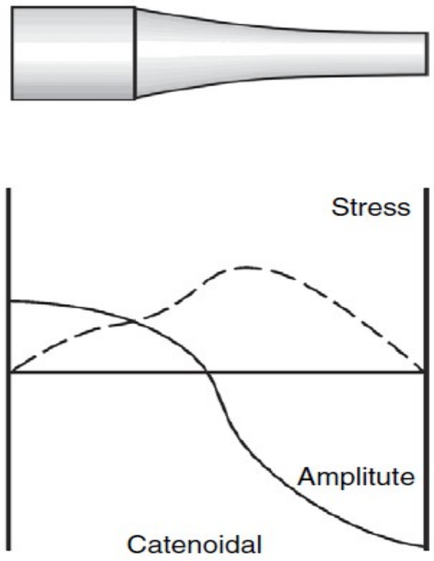

Figure 76: Catenoidal horn profile [19].

Larger welding horns (typically greater than 90 mm in width or in diameter) have slots added to reduce general stress caused by horizontal vibrations. The slots, in effect, break large horns into smaller, individual horns, to ensure uniform amplitude on the horn face and reduce internal stress (Fig. 77).

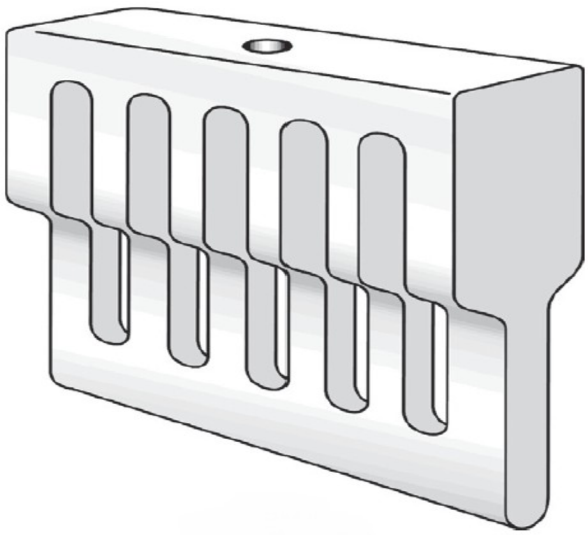

Figure 77: Slotted horn [19].

Horn materials are usually high-strength aluminum alloy, titanium, or hardened steel. Aluminum is a low-cost material which can be machined easily, and which has excellent acoustic properties. For these reasons, it is used for welding large parts and to make prototype horns or horns requiring complex machining. Aluminum may be inappropriate for long-term production applications due to its poor surface hardness and fatigue properties. However, it can be coated or plated with chrome or nickel to help alleviate these problems.

Titanium has good surface hardness and fatigue strength and excellent acoustic properties. However, it is very expensive and difficult to machine. Titanium may also be carbide-coated for high wear applications.

Steel horns can only be used for low amplitude applications due to its low fatigue strength.

Good horn design is a key to successful welding. Horns are precision parts that should only be manufactured by specialists who are adept in acoustical design and testing.

Figure 78: Example of differently shaped ultrasonic horns [23].

The actuator, or welding press, houses the transducer, booster, and horn assembly (also known as “stack”). Its primary purpose is to lower and raise the stack and to apply force on the workpiece in a controlled, repeatable manner; the actuator therefore brings the horn into contact with the parts being welded, applies force, and retracts the horn when the welding is complete.

The anvil (Fig. 79), working in interaction with the sonotrode, produces and shapes the joint and thus is one of the core components of the ultrasonic sealing process. Sealing of films, as mentioned before, requires focusing of the energy by means of the tooling profile, which is mostly mounted to the anvil. Furthermore high rigidity and plane parallelism ensure optimum joint quality. Anvil profiles are essential for the quality of the weld result and are produced to customer requirements and adapted to respective applications. Finally, due to the high thermal sensitivity of all ultrasonic welding systems (par. 2.3.5), water cooled anvils have recently been developed.

Figure 79: Example of differently shaped ultrasonic anvils [23].

Finally, from a control point of view, most ultrasonic welding machines nowadays feature fully programmable, microprocessor control to program and monitor all welding parameters. Some machines monitor and adjust the entire process every millisecond. The controller takes 1000 actual reference weld measurements per second, providing true quality control. The welding modes of time, energy, or distance can be selected from the controller.

Welding by *time* is the most basic mode of operation. The horn brought into contact with the upper part, whilst the ultrasound is activated for the designated time. The power drawn from one cycle to the next can be monitored to give some indication of weld quality and, if it falls outside a range, alarm signals can warn of a potentially defective weld.

Welding by *energy* is based upon closed feedback control, that is, the machine monitors the power drawn as the weld cycle progresses and terminates the weld once the set energy is delivered. 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.
In welding by *distance*, a linear encoder mounted to the actuator accurately measures either the weld collapse or total distance traveled by the welding horn, allowing components to be joined by a specific weld depth. This mode operates independent of time or energy and compensates for any tolerance variation in the molded parts, giving the best guarantee that the same amount of material in the joint is melted each time.

3.3.3 *Mechanisms of energy dissipation and bonding*

Regarding the heating mechanism for the ultrasonic welding of thermoplastic polymers 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, which require heat to enable molecular motion and entanglements.
Both mechanisms occur together but with different intensity. Significant heating because of interfacial friction as shown in Fig. 80 (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 Fig. 80 (right) where heating because of inter molecular friction dominates.
It is also known 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 highdensity 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 $\dot{Q}$ within viscoelastic materials due to sinusoidal oscillating deformation can be described by the following expression, according to:

$$\dot{Q} = \pi f \epsilon_0^2 E'' \qquad (56)$$

where f is the frequency of the oscillating tool, E" is the loss modulus of the material and ε_0 is the strain amplitude. The loss modulus of the thermoplastic is strongly temperature-dependent, so that as the melt or glass transition temperature is approached, the loss modulus increases, and more mechanical energy is converted to thermal energy. Temperature at the weld interface rises rapidly after heating is initiated. 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 ε_0 during the process. For greater welding forces, a significantly enhanced temperature rise in the weld zone has been detected.

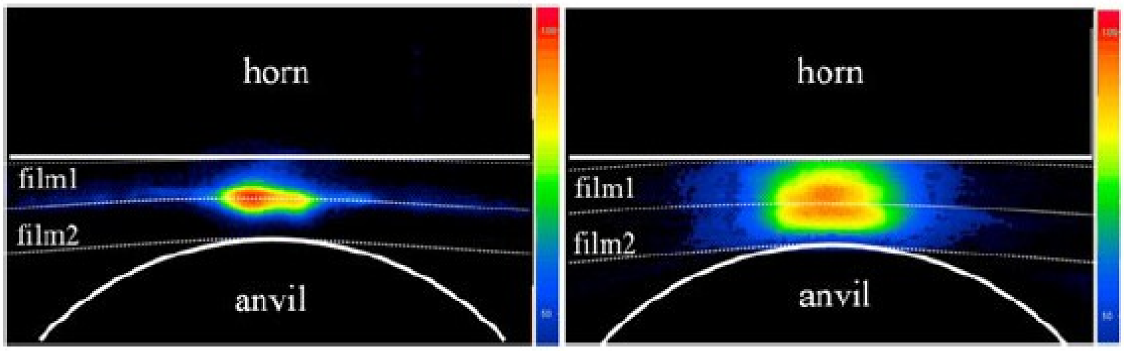

Figure 80: Comparison of typical temperature distributions in the weld zone for different film materials – polyvinylchloride (left) and polypropylene (right) - with heating dominated by interfacial friction (left) and inter molecular friction (right) as measured with an infrared thermograph system [22].

3.3.4 *Process parameters*

The main process parameters in ultrasonic sealing are the sealing time, the amplitude of the horn, the sealing force and the output frequency of the generator.

The weld time is the length of time the horn vibrates per weld cycle, and usually equals the time the horn is actually contacting the part. The correct time for each application is determined by trials. Increasing the weld time generally increases weld strength until an optimal time is reached; further increases result in either decreased weld strength or only a slight increase in strength, whilst at the same time, increasing the possibility of marking the part. Additionally, 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. Referring to Eq. 50, the applied strain is proportional to the vibrational amplitude of the horn, so that heating of the weld interface can be controlled by varying the amplitude of vibration. Amplitude is an important parameter in controlling the squeeze flow rate of the thermoplastic. At high amplitudes, the weld interface is heated at a higher rate; temperature increases, and the molten material flows at a higher rate, leading to increased molecular alignment and lower weld strength. High amplitudes are necessary to initiate melting: amplitudes that are too low produce nonuniform melt initiation and premature melt solidification.

As amplitude is increased, greater amounts of vibrational energy are dissipated in the thermoplastic material, and the parts being welded experience greater stress. In using constant amplitude throughout the welding cycle, the highest amplitude that does not cause excessive damage to the parts being welded is generally used. For semicrystalline polymers such as PE and PP, the effect of amplitude of vibration is much greater than for the amorphous polymers. This is probably due to the greater energy required for melting and welding of the semicrystalline polymers. High-melt-temperature materials and semicrystalline materials generally require higher amplitudes than do amorphous materials.

The amplitude can be adjusted mechanically by changing the booster or horn, or electrically by varying the voltage supplied to the converter. In practice, large amplitude adjustments are made mechanically, while fine adjustments are made electrically.

Amplitude profiling, in which the amplitude is decreased during the welding cycle may been used to achieve good melt flow and consistent, high weld strengths.

The sealing force is normally applied by springs or fluidic actuators. Weld pressure provides the static force necessary to ‘couple ’ the welding horn to the parts so that vibrations may be introduced into them. This same static load ensures that parts are held together as the molten material in the weld solidifies during the last stage of the welding cycle. Determination of optimum pressure is essential for good welding.

In general, while in hot bar welding systems a very high pressure is used that can also not be perfectly constant throughout the surface, in ultrasonic systems it is very important to properly control the welding pressure. Specifically, as in the ultrasonic sealing the welding surface is very limited with respect to that of the conductive systems, even small variations in the force exerted can cause large imbalances in the pressure on the welding area, thus spoiling the end result. This problem could be solved, form a theoretical point of view, by increasing the welding surface; actually, however, this is not feasible as it would require too much power.

Weld pressures that are too low generally result in poor energy transmission or incomplete melt flow, leading to long weld cycles. Increasing the weld force or pressure decreases the weld time necessary to achieve the same displacement. If pressure is too high, the greater melt volume results in molecular alignment in the flow direction and decreased weld strength, as well as the possibility of part marking.

Most ultrasonic welding is performed at a constant pressure or force. On some systems, the force can be altered during the cycle. In force profiling, weld force is decreased during the time that ultrasonic energy is applied to the parts. Decreased weld pressure or force later in the weld cycle reduces the amount of material squeezed out of the joint, allows more time for intermolecular diffusion, reduces molecular orientation, and increases weld strength. For materials like polyamide, which have a low melt viscosity, this can significantly improve weld strength.

In the case of continuous ultrasonic sealing processes such as longitudinal seam sealing, gap-controlled ultrasonic sealing units are used. The gap between horn and anvil is a 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.

Finally, with combined amplitude and force profiling, high amplitudes and forces are used to initiate melting, which are then decreased to reduce molecular alignment with the weld line.

The output frequency of the generator is another crucial parameter since, if working at the same power, there is an inverse proportional relationship between the frequency and amplitude of the sonotrode vibration; this aspect is in turn directly related to the thickness of the film being welded. As the film is folded on itself to form the bag, in transversal welds it is necessary to get from four film thicknesses to one thickness after sealing; the amplitude of the oscillations of the sonotrode must then adapt to the thickness of the film. As an example, if a film that is 80 mm thick is utilised, this implies that the gap between the sonotrode and the anvil will oscillate between 320 mm (four thicknesses) and 80 mm (single thickness); if a film with a thickness of 30 mm is used, the vibration amplitude will be totally different.

The frequency range usually goes from 20 KHz to 80 KHz: usually it is not permitted to go below 20 KHz either because the material will not be subjected to a sufficiently high frequency to trigger welding and because it would enter the hearing range of frequencies and therefore the system would produce a very high noise level; it is also not possible to go over 80 KHz because it would be difficult to get a sufficient vibration amplitude.

High-frequency vibrations (about 70 to 80 KHz) are therefore used primarily to realize the longitudinal welding of the packages, where the film goes from two thicknesses to one and whereby a shorter oscillation amplitude is needed; moreover, high-frequency welding is faster (because the system makes more oscillations in the same amount of time, then the film warms up earlier) and are therefore more suitable in longitudinal welding where the film may advance at 50-60 m/min and must be welded in continuous mode. Low frequency vibrations (about 20-30 KHz) are used instead in transverse welds, where the film goes from four thicknesses to one and therefore a greater oscillation amplitude is required.

3.3.5 *Process stages*

For the intermittent ultrasonic sealing process with force control, there are four main process steps (Fig. 81). 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_b. 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 θ_a to the crystalline melting point θ_k. In step III, the temperature rises from the crystalline melting point 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. Switching off the vibration ensures that the horn sinks into the molten material and reaches the final displacement s_e. After the effective sealing time, the seam cools down in the last step (IV); on reaching the recrystallisation point θ_r of the material the seam becomes almost completely resilient: this typically occurs within several milliseconds. Hence, if the 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.

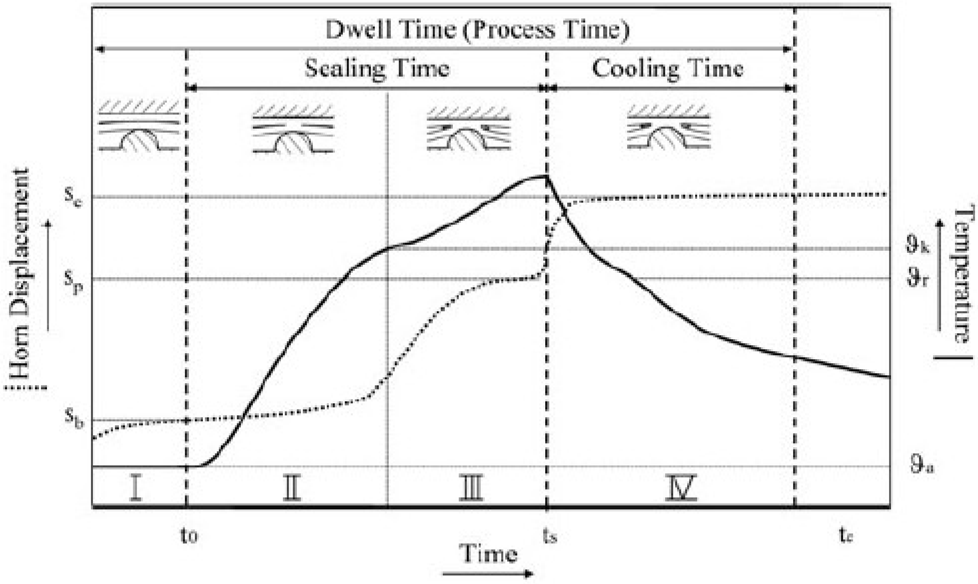

Figure 81: Ultrasonic sealing process stages [22].

It is useful to specify that the Hot-Tack property is defined as the ability of a seam to withstand a mechanical stress when the welding material is still close to the temperature reached during the welding phase. It is a very important property for packaging machines, especially for vertical ones, where also the weight due to the mass of the product loads on the seam.

Hot-Tack property is measured by traction testing at controlled temperatures with special instruments operating according to the specific regulations. In general, the strength vs temperature curves obtained from the tests have the same trend as those obtained in the resistance tests of the already cooled welds (see Fig. 61), but the forces values are significantly lower as they are measured when welds are still hot.

3.4 Experimental comparison between conduction and ultrasonic sealing

3.4.1 *Materials and methods*

Three typical commercial packaging laminates were used for this study. The films consist of a biaxially oriented polyamide (PA) film having a thickness of 15 µm as a carrier layer, and a polyethylene (PE) film having a thickness of 40 µm as a sealing layer (Tab. 4). The composition of the sealing layer differed in the three films (Tab. 7).

A force-controlled ultrasonic laboratory sealing unit with a frequency of 20 kHz 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 Tab. 8.

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 100 mm. A pressure value for ultrasonic sealing with a shaped anvil cannot be calculated, unlike for conduction sealing, because of the radius-shaped anvil.

Finally, the seam strengths were measured with a universal tensile tester (according to DIN 55529) on samples with a width of 15 mm.

	Carrier layer		Sealing layer	
Description	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 7: Packaging films under test [22].

	Process parameters				
Sealing method	Sealing force per length/ sealing pressure	Sealing time	Sealing temperature	Amplitude	Tools
Ultrasonic sealing (20 kHz)	1.5 – 7.5 N/mm	0.05–0.25 s	–	30 μm	Anvil with radius r=2.5 mm
Conduction sealing (permanently heated)	2 MPa	0.5 s	100 – 160 °C	–	Flat sealing bar with PTFE coating

PTFE, polytetrafluoroethylene.

Table 8: Sealing parameters for the test series [22].

3.4.2 *Results*

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 (Fig. 82), which is often characterised by a plateau. 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).

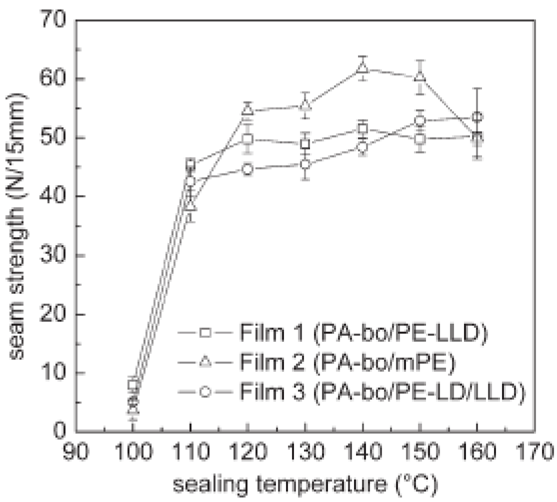

Figure 82: Seam strength as a function of sealing temperature for the three analysed films for conduction sealing with a sealing time of 0.5 s and a sealing pressure of 2N/mm^2, using flat sealing bars [22].

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 (Fig. 83). Film 1 reaches a relative seam strength of about 80% (relative seam strength = seam strength reached by ultrasonic sealing S_{US} / seam strength reached by conduction sealing S_{CS}). The relative seam strength of the two other films is much lower (about 40%). The lower seam strength in ultrasonic sealing compared 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 Fig. 69) 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 notching effects. Regarding the influence of the polymer properties on this phenomenon, it is known 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.

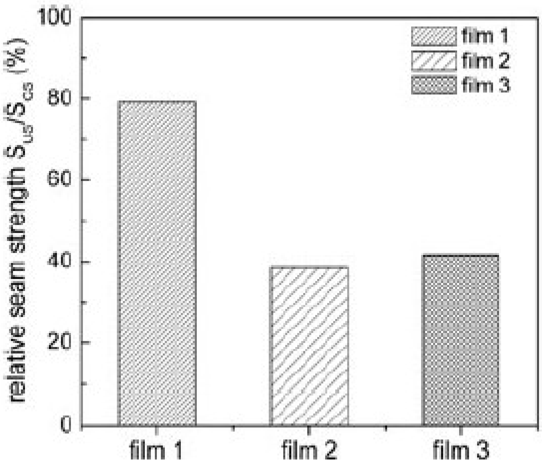

Figure 83: Maximum seam strength in ultrasonic sealing S_{US} relative to conduction sealing S_{CS} [22].

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 (Fig. 84 and 85). For short sealing times, the required sealing force is higher than for long sealing times. There is no typical plateau in ultrasonic sealing seam strength as for conduction sealing.

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.

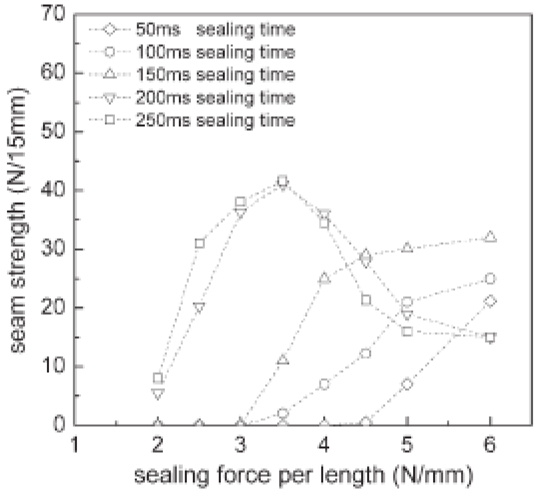

Figure 84: Seam strength of film 1 (ultrasonic sealing) as a function of the sealing force and sealing time, for an amplitude of 30 µm and an energy director with a radius of 2.5mm [22].

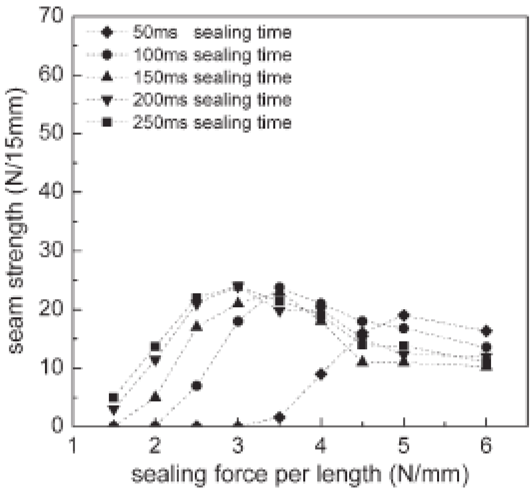

Figure 85: Seam strength of film 2 (ultrasonic sealing) as a function of the sealing force and sealing time, for an amplitude of 30 µm and an energy director with a radius of 2.5mm [22].

Film 3 also reaches a typical local maximum for the seam strength. The seam strength, however, reaches a second maximum when the specific sealing force is increased to 6N/mm (Fig. 86).

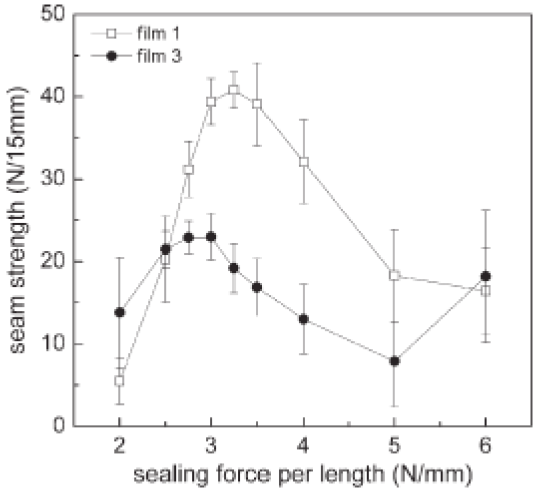

Figure 86: Seam strength of films 1 and 3 at different sealing forces, for 30 μm amplitude and 200 ms sealing time [22].

An explanation for this phenomenon can be seen in following Figures 87 and 88: Fig. 87 illustrates the movement of the horn towards the anvil, which occurs rapidly for high sealing 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.

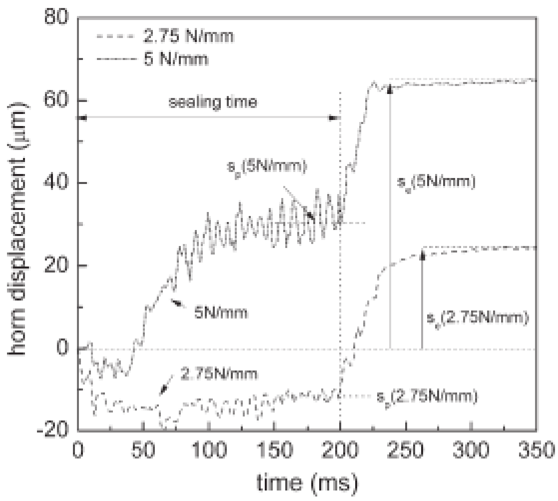

Figure 87: Horn displacement towards the anvil during sealing of film 3 at different sealing forces [22].

For high welding forces, the horn displacement nearly reaches the value 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 Fig. 88. This characteristic melt flow results in material accumulation at the seam sides, especially in Figures 88c and d for the higher sealing forces (5 and 6N/mm, respectively).

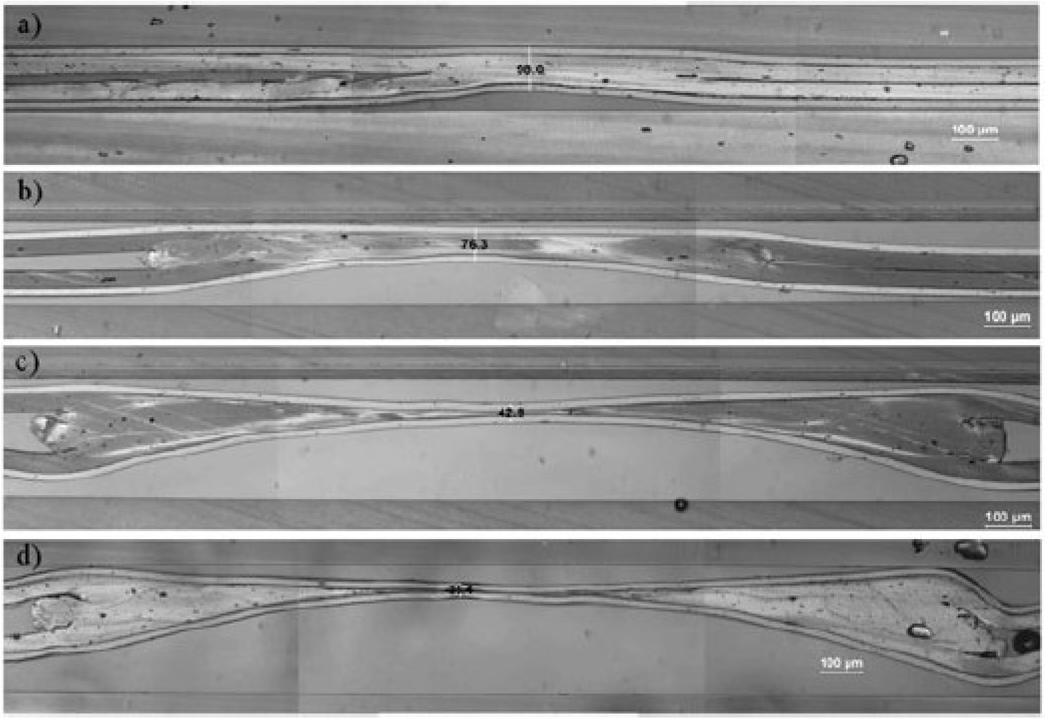

Figure 88: Micrographs of microtome sections of the ultrasonically sealed seams of film 3 for different sealing forces: (a) 2N/mm; (b) 2.75N/mm; (c) 5N/mm; (d) 6N/mm [22].

For higher sealing forces, it is also possible that the polyamide layers become partially interconnected: this may increase the seam strength.

The horn displacement shown in Fig. 87 reaches a stationary level even for high welding forces – this is the stationary plateau s_p in Fig. 81. This plateau s_p is even reached if not all of the sealing material is pushed out, at a specific sealing force of 5N/mm (see Figures 87 and 88c). This indicates a balanced state, and depends on the material properties and process parameters.

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 25–30mm (Fig. 89). This means a thickness reduction of the sealing layer of about 30-38%.

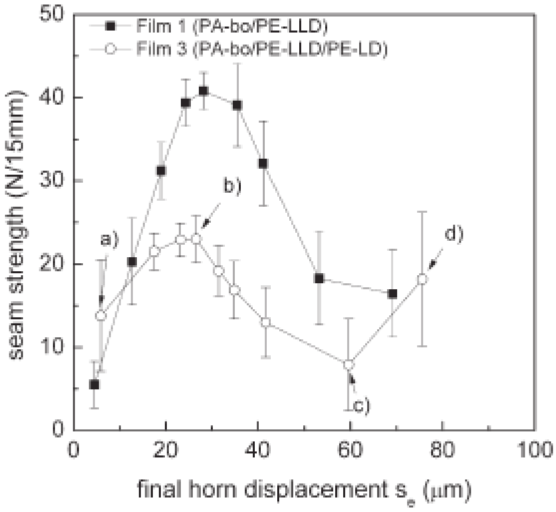

Figure 89: Seam strength as a function of the final horn displacement for films 1 and 3 at 30 µm amplitude and 0.2 s sealing time [22].

3.4.3 I*nfluence 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 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 Fig. 90.

Fig. 90 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).

Regarding the ultrasonic sealing behaviour of contaminated seams it is known that most of the contamination do not significantly influence the seam strength. Furthermore, the quality of the seam depends on the specific contaminant products and on the types of packaging films used. Ultrasonic sealing mainly has advantages, with respect to conduction sealing, for loose materials such as powders, coffee and flour.

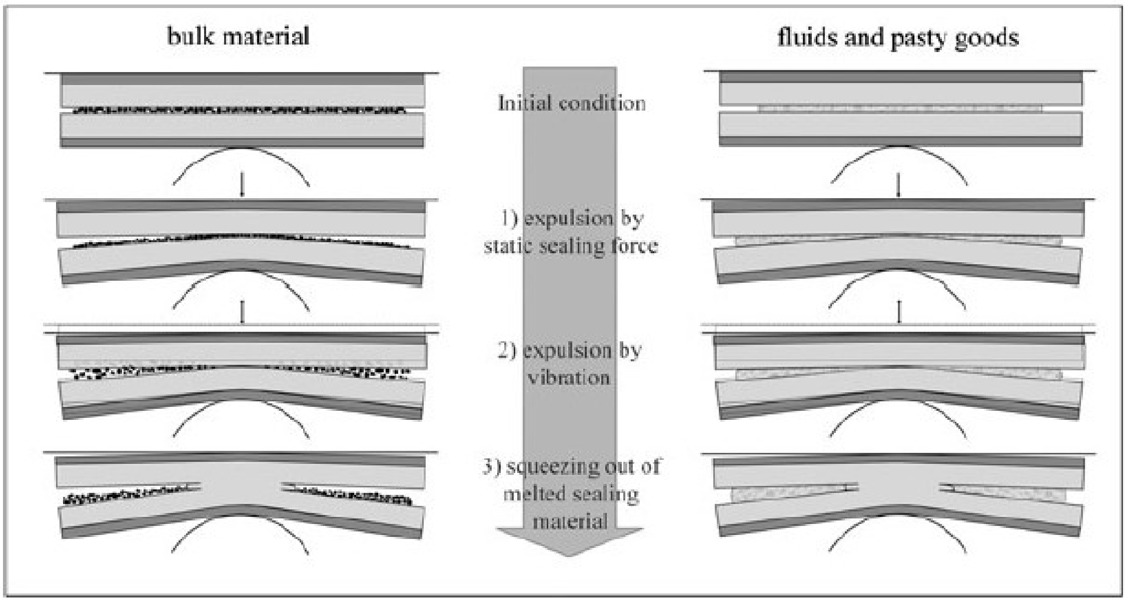

Figure 90: Principle of expulsion of product contamination during ultrasonic sealing[22].

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. The products were spread manually over an area of about 100 x 10mm. 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 Tab. 9. It is important to note that these amounts represent a worst-case scenario for completely contaminated seams.

	Contaminant product					
	Bulk materials		Fluids and pasty products			
	Wheat flour	Coffee powder	Potato chips	Olive oil	Salad dressing	Grated cheese
Amount	0.25g	0.1g	Circa 3g	0.3g	2g	Circa 2g

Table 9: Type and amount of products that have been investigated [22].

In Fig. 91 a comparison between the three PA/PE films used for the tests is presented (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 image 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%. The standardised seam strengths of the other films are only around or below 50%. 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 25N/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, the sealing performance on contaminated seams is relatively low.

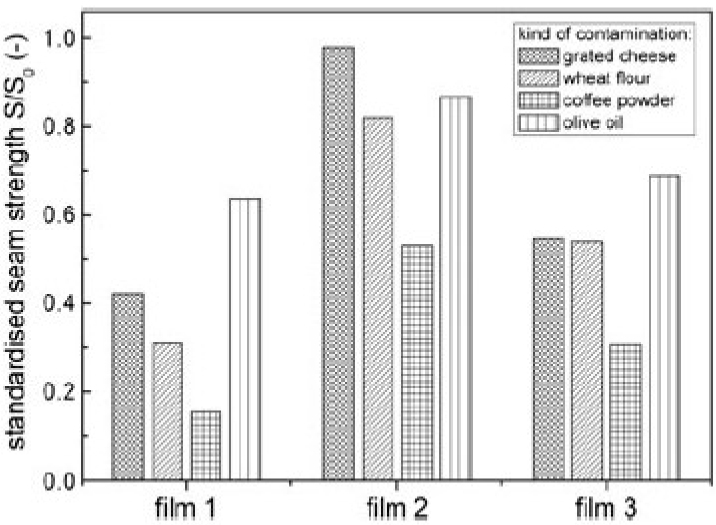

Figure 91: Comparison of the standardised seam strength of contaminated seams of the three packaging films for ultrasonic sealing with different contaminants [22].

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 92c. 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. 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; however it is verified that, for higher sealing forces, the effect of expulsion of loose material and the resulting standardised seam strength are even increasing.

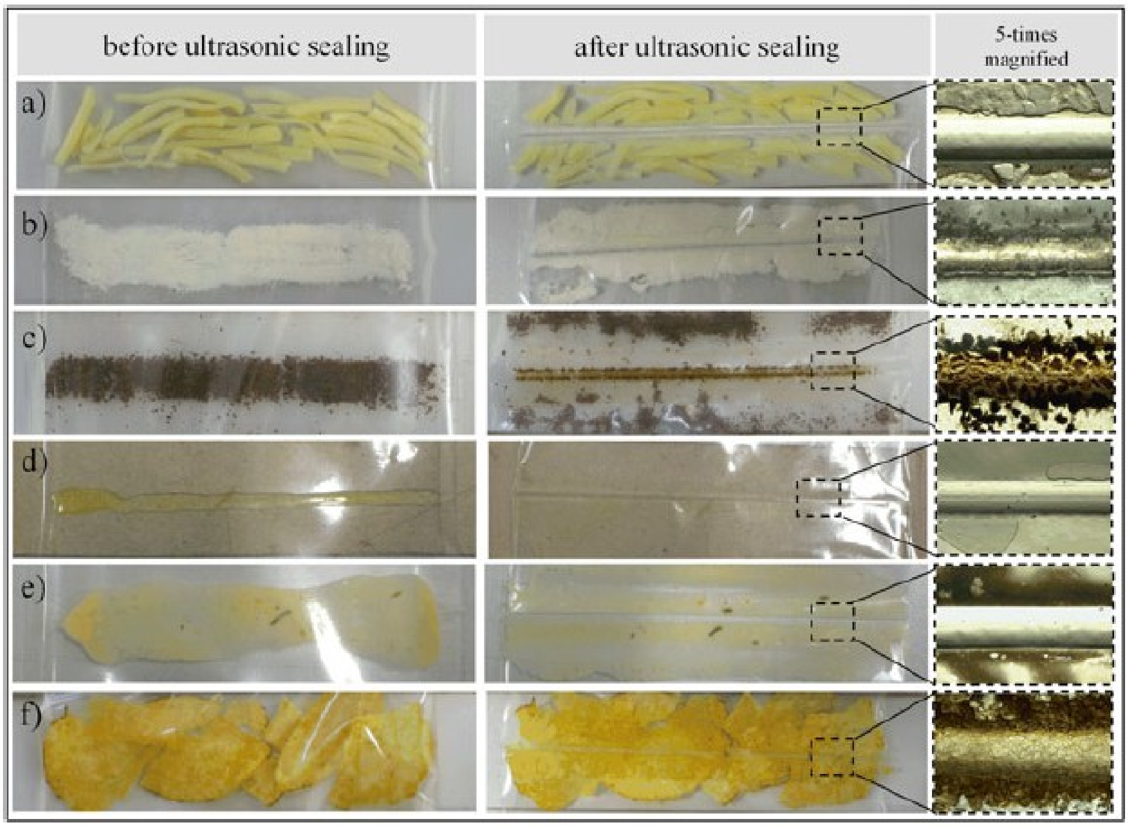

Figure 92: Top view of contaminated seams before and after ultrasonic sealing, contaminated with (a) grated cheese, (b) wheat flour, (c) coffee powder, (d) olive oil, (e) salad dressing and (f) potato chips [22].

3.4.4 E*nergy efficiency*

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 meter was installed to measure the effective energy consumption. 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 (15/40µm) and a polyester-aluminium-polyethylene (PET/ALU/PE) laminate with thicknesses of 12, 7 and 80 µm for the various layers.

For conduction sealing, the sealing temperature and sealing time were varied in order to find an optimal setting. 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 300ms. For this sealing time, only a maximum output of 120 bags per minute was possible for this film.

Regarding 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 1000–1200N. In Fig. 93 the results for both films in the case of ultrasonic sealing method show a typical behaviour for the dependency of the seam strength on sealing force, as already discussed earlier.

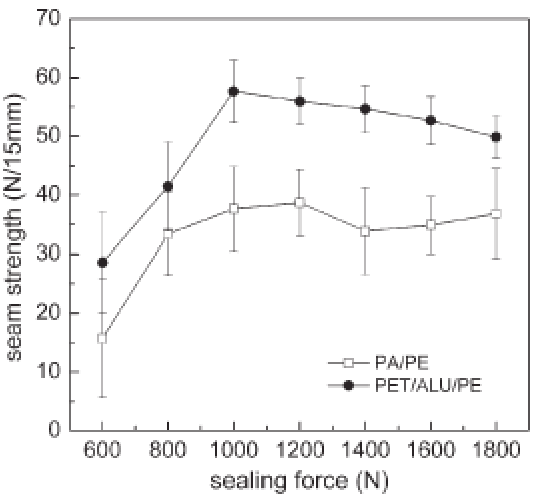

Figure 93: Seam strength as a function of sealing force for ultrasonic sealing of polyamide/polyethylene and PET/ALU/PE laminates [22].

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 about 75% of the seam strength for conduction sealing.

For the tests, a sealing force value of 1000N was preferred in order to achieve a minimum energy consumption, which rises with increasing sealing force (Fig. 94).

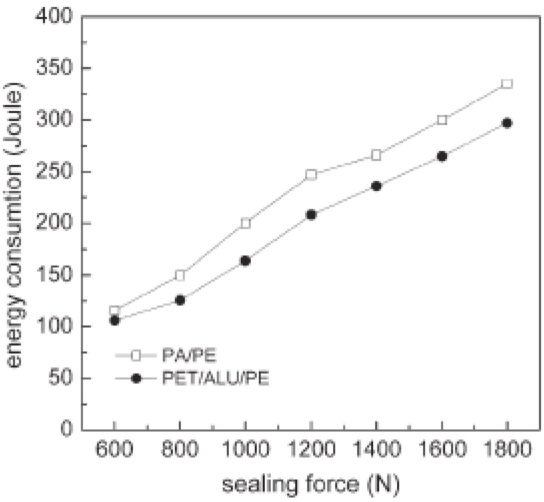

Figure 94: Energy consumption as a function of sealing force for ultrasonic sealing of polyamide/polyethylene and PET/ALU/PE laminates [22].

The results of the test series in Fig. 95 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; for this reason the energy consumption for conduction sealing strongly depends on the machine speed and is reduced at increased machine output: in this case, in fact, the ratio of the sealing time on the whole time of cycle increases and hence the relative losses because of convection and radiation decrease. For the PA/PE film in Fig. 95, the energy consumption even reaches the same level for both sealing methods at high machine output.

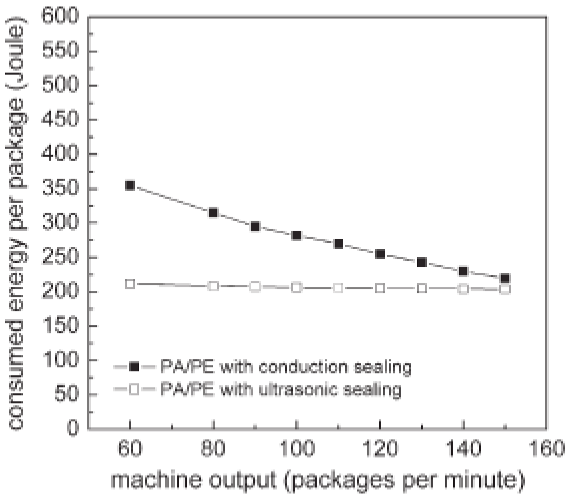

Figure 95: Energy consumption for conductive sealing and ultrasonic sealing as a function of machine output for a polyamide/polyethylene laminate [22].

The difference in energy consumption between ultrasonic and conduction sealing highly depends on the packaging film as indicated in Fig. 96. For the PET/ALU/PE laminate the energy consumption for ultrasonic sealing is only 30–40% of that for conduction sealing.

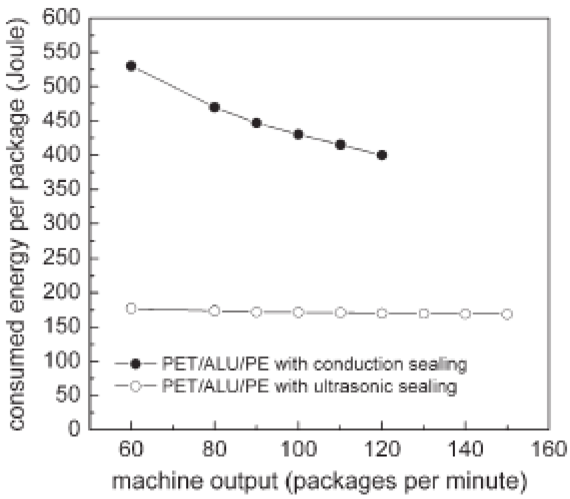

Figure 96: Energy consumption for conductive and ultrasonic sealing as a function of machine output for a PET/ALU/PE laminate (layer thicknesses: 12/7/80 μm) [22].

By using aluminium as a barrier layer, it 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 instead, the heat is dissipated within the sealing layers (Fig. 38), 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 may be possible, with respect to conduction sealing, especially for thick packaging materials and low machine output.

3.5 Final considerations about conduction and ultrasonic sealing methods

As exposed in this chapter, the ultrasonic sealing method has several advantages over conduction sealing, however, it is not the best choice for every application. In this paragraph the most important positive aspects of the ultrasonic method are summarized together with the negative ones in order to give a clear idea of in which applications may be convenient to use a welding method based on ultrasonic technology.

Cold Sealing: a drawback associated with the often-used hot sealing method is the negative influence on product quality by the required sealing heat: the high temperature of the sealing jaws can cause product damage. In the ultrasonic sealing method instead, the sealing jaws are not heated making it ideal for heat sensitive products. Furthermore, the melting of heat sensitive products results in contamination of the sealing jaws and therefore more cleaning time. With ultrasonic sealing the product does not melt leading to reduced product waste and maintenance.

Increased Productivity: compared to conventional heat sealing systems, ultrasonic sealing has the potential to increase production line speed significantly. Since the film is only heated in the relevant area, the seam cools down very fast. This allows the seams to be immediately subjected to product load after joining, reducing processing time. Short sealing times, as well the elimination of warm-up and cooling time further increase production efficiency.

Sealing Through Product: during the packaging process the product can contaminate the sealing area of the bag, preventing it from being properly sealed. However, by using ultrasonic sealing it is possible to seal through a wide variety of products and liquids reducing the occurrence of this issue.

Reduced Production Costs: in general, ultrasonic sealing helps reducing production costs in many different ways. This welding method uses less packaging material, because the package can be sealed with a narrow seam width and requires less space above the product level: with vertical FFS machines, up to 16 millimeters of film can be saved per package in terms of bag length. As already said, it avoids improperly sealed bags by sealing through product. The sealing process requires less energy because ultrasonic vibration is only applied at the exact moment of sealing; moreover the temperature needed for welding purposes is generated inside the film in the actual sealed seams. This means, for example, an horizontal flow wrapping machine requires only 4.0 joules for sealing compared to hot sealing with 6.7 joules. Additionally, manufacturers can further benefit from the fact that there is no risk of heat-related damage to materials or products in the event of machine stoppages. A popular alternative in the past, when packaging heat-sensitive products like chocolate, was to use cold sealing film to prevent products from melting. One disadvantage of this approach is the limited storage life of the film, which tends to stick together or to the product. Furthermore, the relatively high costs involved with cold sealing film have encouraged manufacturers to consider alternative sealing methods like ultrasonic technology. As a further benefit the “cold” ultrasonic sealing technology also eliminates the need to clean hot sealing jaws. By reducing the issue of film sticking to the heated jaws, ultrasonic technology ensures that there is less material residue after sealing and fewer defective packages, all of which can help to reduce equipment downtime. As a result, manufacturers can see significantly increased operating times and a reduction in material waste.

About the drawbacks of the ultrasonic sealing technology, the most important ones are summarized hereafter.

Reduced seam strength: for some laminated films it is quite difficult for ultrasonic sealing to produce seam strengths comparable to those obtainable with conduction sealing; in particular the quality of the sealed welds significantly depends on the properties of the sealing materials.

Sonotrode Wear: the sonotrode presents the wear problem: as it is made with high precision finishes to ensure a vibration with a very small wavelength, as soon as the piece is re-machined after wear, a change of a few hundredths of millimeter is enough to ruin the characteristics of the sonotrode. In case of excessive wear, the only solution is to replace the component.

Sensitivity to Thermal Expansion: when welding with particularly thin films the relative position between the sonotrode and the anvil is sensitive to temperature variations. As an example, 18 μm thick films exist and in this case the sonotrode must vibrate between 64 μm (four thicknesses) and 18 μm: these are very small values, so it is sufficient that the sonotrode and the anvil expand a little to ruin the welding. In ultrasonic welding in fact, it is recommended to use films with a thickness greater than 30 μm because otherwise the dimensional variations due to thermal expansion will be comparable to film thickness: in general, it is necessary to verify that between the sonotrode and the anvil always remain at least 30-40 μm, if these components dilate too much instead, the gap goes to zero and the welding system will cut the film instead of sealing it.

It is worth noting that ultrasonic welding, although it may also be considered a "cold" welding, is still a method that involves the development of heat inside the film in contact with the sonotrode and the anvil: therefore it is possible that a small thermal expansion arises in the aforementioned components. The problem is that the sizes are hundredths of millimeter, so the construction tolerances required by ultrasonic welding are not the typical tolerances of the packaging industry, which is used to high speed but not to micrometric precision.

Finally, it is interesting to note the differences in behavior of the two welding methods when the type of film varies. In particular, in the case of films not contaminated by the product, said that in general, as aforementioned, the conduction welding is in any case more resistant than the ultrasonic one, with ultrasonic welding it is possible to obtain more tough joints with films having a wide melt range and a viscosity that grows little with increasing temperature: between the three tested films, the best one is in fact the first, having an LLDPE sealing layer. As regards the case of films contaminated by the product, it is possible to notice a dependence of the welding toughness on the specific type of product, however, in general, the film with the best results is the one which presents an m-PE sealing layer. Regarding the energy consumption to make the welds, it has been showed that a film with aluminum layer requires much more energy with conduction welding than with the ultrasonic one because the aluminum layer tends to disperse heat sideways.

In the end, considering the ultrasonic welding, given the same sealing layer composition of the film, the welding efficiency increases for thicker layers because of the more effective energy dissipation.

In conclusion, it can be stated that ultrasonic sealing is an interesting alternative to conduction sealing but higher investment cost and often higher complexity of process integration have to be weighed up against the benefits.

CONCLUSIONS

In this thesis firstly an innovative method about the sizing of the motor-reducer unit is evaluated which, if applied in the case of electric axes of food packaging machines, allows to maximize aspects such as flexibility, i.e. the ability to pack products of different dimensions, as well as production volumes; furthermore two of the most important sealing methods, conduction and ultrasonic welding, were examined in depth, highlighting how the second one is more convenient than the first one if the application requires a welding solution for heat-sensitive products, high production line speed, eventually sealing through the product and/or reduced production costs.

Regarding future developments in food packaging, an important aspect is the tendency to use films increasingly thin, in order to reduce waste of material, and ecological, such as biobased and paperbased films, to reduce the environmental impact. In particular, biobased films are made of renewable biopolymers which can reduce dependency on fossil resources. The use of biopolymers does not change the properties of the packaging film or laminate (relative to conventional fossil based films made of polyethylene, polypropylene, polyester or polyamide). All these properties are retained, including processability, optical performance, sealability, barrier and mechanical properties. As for the paperbased films instead, durable paper packaging with a natural look and feel are becoming more and more requested: thanks to the use of barrier laminates for food products, this type of film optimally protects the contents while accentuating the freshness and quality of the product; the attractive appearance and natural haptics of paper packaging improve brand image at the point of sale.

It is possible to notice increasing needs in terms of productivity (the world population is growing and this increases the requirement of packaged food), measurable in particular as *production density* of the machines, i.e. maximum productivity compared to the volume of the machine: this represents a new parameter of evaluation of food packaging machines and it is of great importance as the factories often have some production processes that are not movable at other points of the plant and this implies that other machines must be able to be placed in a specific and limited area.

Furthermore, modified atmosphere food packaging (MAP) is becoming more and more widespread, in order both to increase the shelf life and retain the quality of food products; in the following a summary table (Tab. 10) on the applications of MAP.

Examples of Gas Mixtures for Selected Food Products

Product	Temperature (°C)	O_2 (%)	CO_2 (%)	N_2 (%)
Meat products				
Fresh red meat	0–2	40–80	20	Balance
Cured meat	1–3	0	30	70
Pork	0–2	40–80	20	Balance
Offal	0–1	40	50	10
Poultry	0–2	0	20–100	Balance
Fish				
White fish	0–2	30	40	30
Oily fish	0–2	0	60	40
Salmon	0–2	20	60	20
Scampi	0–2	30	40	30
Shrimp	0–2	30	40	30
Plant products				
Apples	0–4	1–3	0–3	Balance
Broccoli	0–1	3–5	10–15	Balance
Celery	2–5	4–6	3–5	Balance
Lettuce	<5	2–3	5–6	Balance
Tomatoes	7–12	4	4	Balance
Baked products				
Bread	RT[a]		60	40
Cakes	RT		60	40
Crumpets	RT		60	40
Crepes	RT		60	40
Fruit pies	RT		60	40
Pita bread	RT		60	40
Pasta and ready meals				
Pasta	4		80	20
Lasagna	2–4		70	30
Pizza	5		50	50
Quiche	5		50	50
Sausage rolls	4		80	20

[a] Room temperature; staling is accelerated at refrigerated temperatures.

Table 10: Applications of MAP [18].

Finally, a novelty that is currently spreading is constituted by the so-called "magnetic carts". These are a mechatronic system that guarantees flexibility and modularity for the transport of all types of material. One of the major manufacturers of this system is Beckhoff, which produces the "XTS" (eXtended Transportion System); other manufacturers producing equivalent systems are Rockwell and B&R. This solution consists of electromagnetic tracks which, if suitably controlled, can move the so-called "movers" (which host some magnets inside them to react to the field created by the tracks) (Fig. 97 - 98); this is the evolution of the linear motor concept: movers can move endlessly, without cables (they are passive elements) and the mover number is unlimited.

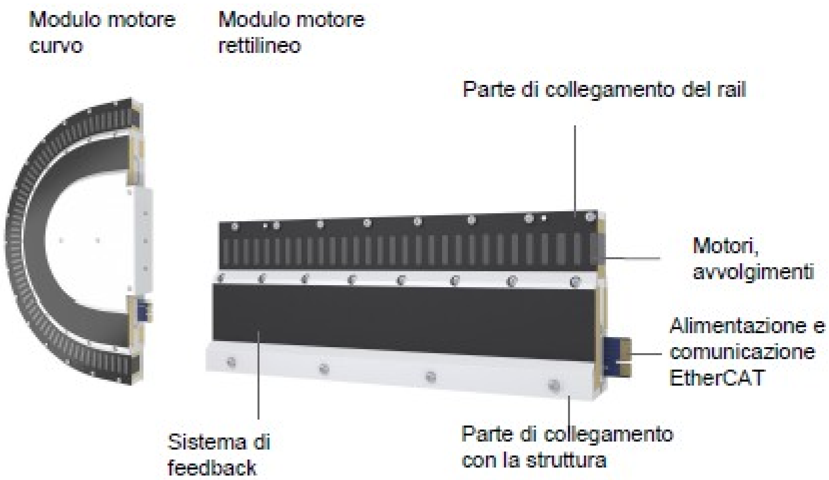

Figure 97: Examples of electromagnetic tracks, curved and rectilinear [26].

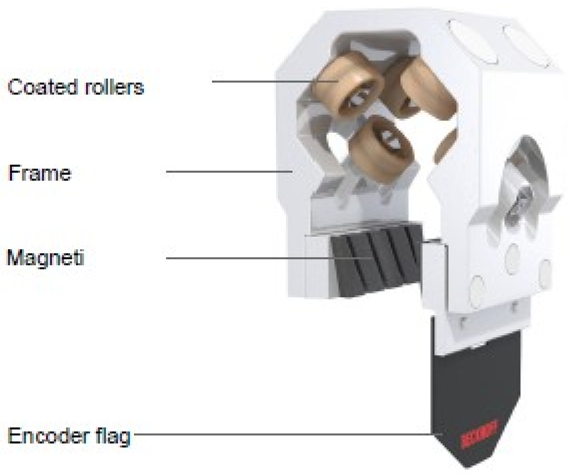

Figure 98: Example of mover [26].

XTS is a flexible and scalable system. The movers can be moved independently up to a maximum speed of 4m/s, with accelerations up to 10 g; furthermore each single mover can exert a constant force of 30 N and a peak force of 100 N, where the duration of the application of the 100 N depends on the thermal model (i^2t) of the system that protects the modular drives from excessive current absorption.
Movers can be moved simultaneously and completely independently of each other: in particular it is possible to put movers together (so forming groups), synchronize their movements with external events, etc.
Furthermore, a feedback system is directly integrated into every motor module so each single motor detects the presence of the encoder flag of the movers on its path (it is an absolute encoder, the homing procedure is therefore not necessary), the control loops guarantee precise and repetitive positioning (repeatability < 10 µm, absolute accuracy < 250 µm), movement parameters are freely adjustable and modifiable even during functioning, every single mover is seen as a real axis. In addition, XTS is a modular system, composed of single tracks of different shapes (straight or curved) that join each other to compose a path with a complex shape: the form of the transport system can therefore be adapted to the specific needs of the application.
All this means that these systems provide total freedom of movement in transport machines, making the mechanical design of the format change a lot easier and quicker.
Just to provide a couple of examples of the potential of these systems, the magnetic carts can be used instead of the lug chains within horizontal flowpack machines, in this way they allow to change the format simply by changing the recipe from plc, without having to mechanically replace the whole chain in order to have a different gap between the various lugs; another field of application are the blades for alignment by rows: as specified in the first Chapter, when products exit the oven or cooling tunnel, they are never perfectly aligned, therefore, these blades ensure that the products, by leaning on them, are aligned by rows and then the blades “run away” and reappear again at the same point to align the next row of products; in case of a format change, if the blades are moved by an XTS system it is simple and quick to adapt their movements to the new type of product chosen.

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