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DESIGN FOR IMPROVED TOOLING THROUGH AN UNDERSTANDING OF MACHINE-MATERIAL INTERACTION

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Abstract

Market price demands and legislation are forcing fast-moving consumer goods manufacturers to use thinner and lighter-weight packaging materials. As a consequence, machinery manufacturers are required to produce packaging systems which are capable of handling a wide variety of materials as well as the necessary variation in pack sizes. However, their ability to achieve this is frustrated by a number of factors: machines have evolved incrementally over time and are sensitive to variations in materials; a lack of understanding of which material properties are important and what values are necessary for successful processing; and the trial and error development processes adopted by many small medium-sized enterprises. To overcome these important issues this paper presents the processes of investigating and modelling the critical machine-material interactions occurring in packaging systems. The critical aspects of building a complete process model are discussed and two generic industrial cases are described in detail. In particular, the use of the models for designing tooling, determining machine settings, reverse engineering material properties and pack design are discussed.

Keywords: performance limits, machines, materials, redesign

1.0 Introduction

In the past machine systems were generally designed to accommodate or handle either a limited range of products or in some cases a specific product [1]. In contrast to this, today's machinery manufacturers are required to produce machines with ever increasing performance envelopes and range of capabilities. In addition to delivering these extended capabilities, the machinery is often required to be capable of handling a variety of different production materials. Furthermore, it is likely that these materials will, during the life of the machine, be the subject of considerable reengineering and development.

These market pressures and process issues are particularly prevalent in the fast moving consumer goods (FMCG) sector. Here much of the packaging and processing equipment has been developed by small medium-sized engineering companies (SMEs). Many of these machines have evolved incrementally over time to meet the changing needs of the customer, and much of the equipment retains the bulk of its original design principles. As a consequence of this, considerable design knowledge and understanding may well be unavailable. Furthermore, a large proportion of the machines may be operating near the fundamental limits of their performance as dictated by their design principles [2]. This can make it particularly difficult for manufacturers to configure machines which are capable of meeting the increasing performance requirements and accommodating a wide range of product and material variants. In practice, machines which are operating near their performance limits become increasingly sensitive to changes in operating conditions, product and materials [2]. This can result in significant losses in process efficiency and even considerable process downtime.

The issue of changes in materials is becoming increasingly important in the FMCG sector where there are increasing pressures to reduce packaging material consumption and waste [3]. For these reasons material suppliers are developing thinner lighter-weight materials which are more environmentally friendly. In general, these materials have considerably different overall properties when compared to the more traditional materials. Although, new production techniques and composite materials allow packaging materials to be specified with certain desired properties, it is not always clear what material properties are important and what values are necessary for the purpose of processing.

In order to address these issues many manufacturers undertake considerable evaluation trials testing of machines and particular materials. Furthermore, the overall production processes of many machinery manufacturers now incorporate a significant commissioning phase. This typically involves production trials on the customer's site during which the machine and processes are fine tuned to achieve acceptable production rates and process efficiency. This approach carries a considerable overhead for the machinery manufacturer and is not a long term sustainable activity. If only because the process does not support the development of the fundamental understanding necessary for the organisation to develop the next generation of machinery.

All of the aforementioned issues; material and product variation, incremental machine development and continual fine-tuning for specific applications, are considerably exacerbated by today's global market places. Even the smallest of machinery manufacturers is trading with customers across many different continents, and these same customers are purchasing and procuring materials from a similar variety of suppliers distributed across the globe. The consequences of this are that material and product variations are likely to increase as will the need for commissioning machine systems and change parts at the customer's site. However, in order to remain competitive and profitable it is necessary to reduce or even eliminate the need for commissioning particularly in the case of change parts. For example, a change part such as a bespoke former might normally make a significant contribution to profit, but if it is necessary for an engineer to visit the customer and commission this shoulder the profit is at best significantly reduced, if not totally wiped out.

1.1 Understanding machine-material interaction

For the reasons discussed in the previous section it is no longer sufficient for the machinery designer to consider the machine system and solely its functional performance. It is necessary to also consider and understand the interactions occurring at the machine-material interfaces. In fact, recent work involving the design of high-speed machinery has shown that the limits of many processes can be attributed to the operations where interactions occur between machine and materials [4]. As stated in the previous section these issues are a particular challenge for the producers of machinery for the FMCG sector. For example, for almost all of the common packaging operations, a large number of interactions occur during the formation of the pack, insertion of the product, and closing and sealing of the pack.

These interactions typically involve a wide variety of machine elements including standard machine parts and intricate tooling. Many processes may fail because the material properties have changed and as such the interaction with the tooling elements is no longer successful. For example, failure may occur where the surface properties of the material results in excessive frictional forces, or when the stiffness of the material is too high resulting in the material not taking up the desired form. As a consequence of this, it is particularly important that the nature of these interactions is well understood and taken into account. This is necessary to support the design of change parts and tooling which can handle the new thinner lighter-weight materials, and to understand the performance envelope of particular tooling configurations. In addition to this, a fundamental understanding is essential in the long-term for the design of machines and processes which are less sensitive to changes in processing conditions and also capable of meeting the increased performance requirements.

To address this important issue, the work reported in this paper presents the investigation of two common packaging operations where machine-material interactions pose a significant design challenge. These operations involve the high speed production of cartons and the production of pouch bags.

1.2 Carton production

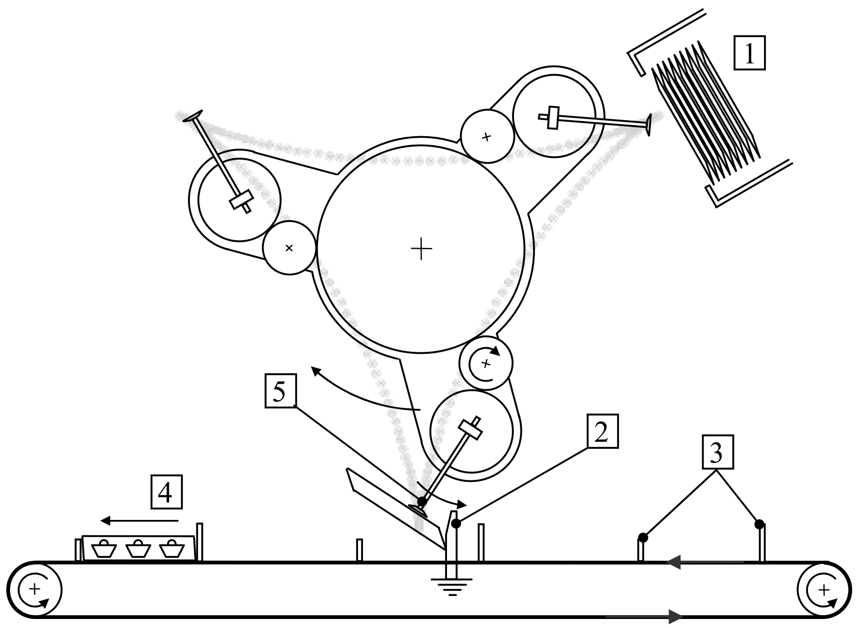

Figure 1 A schematic view of an end-loading cartoning machine

Cartons to hold product are often supplied in the form of a skillet A skillet is a partially folded carton which takes the form of a flattened parallelogram. A common method of erecting a skillet is by use of an epicyclic mechanism. A typical three station configuration is shown in figure 1. This is capable of achieving production rates in excess of 200 CPM (cartons per minute). In the three-station mechanism, idler gears rotate clockwise against a fixed sun gear and this causes the three arms of the mechanism to rotate clockwise while the planet gears revolve in an anticlockwise direction. The locus of movement of the suction cups attached to the planets is illustrated by grey dots. Wider spaced dots indicate higher velocities. The kinematic properties of the epicylic mechanism are ideal for skillet picking and erecting, since the velocity of the effector is at a minimum at the two critical transfer points. In operation, a skillet is drawn from a feed magazine (1) and held securely by vacuum. It is then accelerated and rotated anticlockwise towards a fixed backstop (2). The leading edge of the skillet is forced into contact with the backstop by the movement of the arm and this initiates the erection process. As the skillet nears the base of the backstop, it is approached by the moving lugs (3) which are attached to a conveyor. The impact with the moving lugs completes the erection process and when the arm is at bottom-dead-centre, the vacuum is released. The erected carton is then held between the moving lugs and filled with product (4) before being transported to the downstream processes.

This process and the subsequent product packing operations are critically dependent upon the successful opening of the skillet. Obtaining reliable and repeatable opening is therefore particularly important, but it can be a complicated and time-consuming task when new carton sizes or materials need to be accommodated. One of the reasons for this is the current commissioning processes of many machinery manufacturers. This typically involves systematically reducing production speed and observing the number of failures during each production run, until successful opening is achieved. Although there is some variation in the tooling setup (for example the inclination of the arms (5) and the position of the vacuum cups) the effect on performance is not well understood, and hence not usually explored. This commissioning process frequently results in relatively low production rates, or greater production rates and machines which are very sensitive to set up changes and variability in materials, such as those arising from changes in environmental conditions [5]. In extreme cases, successful opening still cannot be reliably achieved and the material has to be changed. However, it is often not always clear what properties need to be changed and what the effect might be in terms of production capabilities and cost.

These issues lead to a number of specific challenges for the manufacturers of this class of packaging machine. They need to:

- Design variable tooling capable of being altered to improve the ease of processing for different pack sizes and materials.
- Develop formal procedures for determining machine set up (changeover). This is becoming more important with the increased use of servo drives which allow for automated changeover using pre-programmed settings.
- Understand the critical material properties and their impact on process efficacy such that, production rates can be achieved by altering the necessary material properties.

1.3 Bag production

In the production of bags or pouches, a process known as ‘form-fill and seal’ is often employed. A schematic overview of a typical machine system is shown in figure 2. This process involves the formation of a bag from a flat web of packaging material. This bag is then filled with product and sealed. Material is drawn from the flat roll (1) and over the forming shoulder (2) to create a tubular shape around the product feed tube (3). The edges of the film are overlapped and are either heat sealed or glued to form a tube into which the product can be inserted in measured quantities. The tube of packaging material is then cross-sealed to form a closed bag (4). The final seal also forms the base seal of the next bag.

The successful creation of the pack is dependent upon the performance of the forming shoulder, which is entirely dependent upon the surface geometry of the shoulder (2). A different former is required for not only different bag widths but also different materials and sometimes the different surfaces on print finishes. For example, the lower portion of figure 2 shows various former geometries for the same size of bag. Here the key parameter is what can be thought of as the height to radius ratio (reducing from left to right in figure 2). Effectively, altering the height of the former has the effect of reducing the included angle between the vertical portion of the former and the fin (rear of the shoulder). The primary reason for altering the height to radius ratio is to reduce the force necessary to draw the material over the shoulder and hence the magnitude of the tension in the material. Such an approach is common practice within the industry, however, there is little or no quantitative data. Rather manufacturers produce a number of different shoulders and undertake production trials to determine the most suitable one.

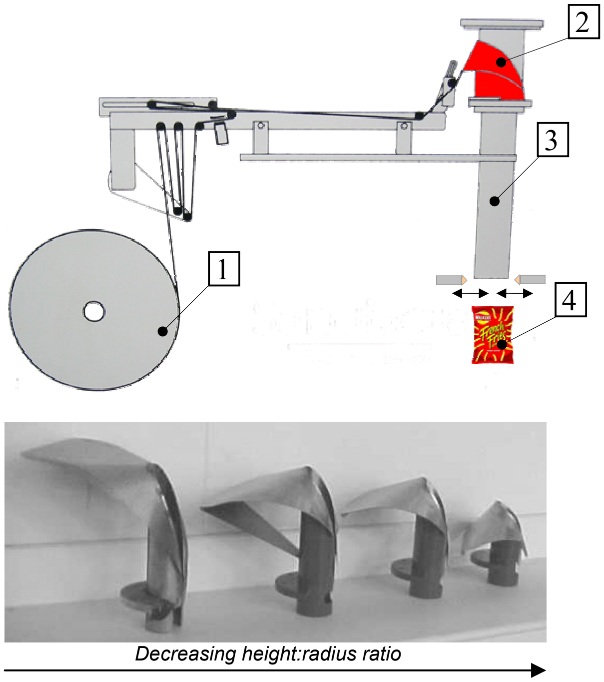

Figure 2 A schematic view of a vertical form-fill and seal machine

The matching of shoulder geometry to material is further complicated by the method of fabrication. Formers are typically constructed from a flat metal sheet cut into in two parts along a bending curve. The portion below the curve is rolled into a cylinder to form the tube, whilst the section above the bending curve is formed around the top of the tube. The shape of the resulting forming shoulder depends on the bending curve and the radius of the tube. The current production method results in a degree of imprecision in the final geometry of the forming shoulder. Such errors or deviations are corrected during trial-and-error testing by the engineers. This typically involves slight alterations to the surface of the former.

These difficulties lead to a number of general issues facing the manufacturers of vertical-form fill and seal machines. They need to:

- Develop the quantitative understanding necessary to match materials to specific shoulder configurations (right first time).

- Implement design procedures to improve the accuracy and repeatability of shoulders produced. This is particularly important for the creation of repeatable change parts.

2.0 Investigating machine-material interaction

Consideration is given here to the machine-material interactions that occur during a number of complex operations commonly used in the packaging of fast moving consumer goods.

Although two specific cases have been considered, the methodology and techniques presented have been created from the results of the investigation of a large number of packaging processes.

Although an overall methodology for understanding machine-material interaction has been previously reported [6], this paper presents a more detailed overview of the important elements of modelling and the subsequent use of the models for the tasks of the design of tooling and determination of the operational settings for machine setup.

Prior to the creation of computer based models of the machine, process, product or materials, it is firstly important to identify and explore the interactions. In general this process can only be effectively undertaken through practical studies and investigation of the whole machine system and the materials. This may involve full production trials and the measurements of a variety of material properties and machine elements. In particular it is often necessary to measure:

- Material properties which influence the structural behaviour and response of the packaging material.
- Dimensions and surface properties of tooling, and where moving parts are considered, velocities and accelerations.
- Properties of both the materials and tooling which impact upon the effect of the interactions, such as frictional properties, loads and deformations.

Once the full range of interactions has been considered, it is possible to establish the requirements of modelling and select appropriate modelling tools. The process has been undertaken for the two cases considered and the results are summarised in the following sections.

2.1 Machine-material interactions occurring during carton production

The practical investigation of the machine-material interactions during carton erection revealed that the critical interaction is the impact of the carton with the lug, shown as (2) in figure 1. Here successful interaction resulted in the skillet opening fully. Through the undertaking of a wide range of production trials involving different carton sizes and materials a number of critical factors were identified:

- The ratio of material stiffness to the crease stiffness. Cartons are initially creased to enable them to fold in the desired manner. The properties of this crease affect the performance of the carton both during production and life.
- The initial opening (plim) of the skillet [5]. This is defined as the amount by which the carton opens when unrestrained.
- The angle of incidence (angle of attack) of the skillet with the lug. For larger carton sizes, the position of the lug (figure 1 (2)) is moved upstream. As a consequence, for large cartons, the angle of incidence is reduced tending towards the horizontal.
- Aerodynamic effects. At higher production speeds the aerodynamic forces on the carton cause it to deflect and distort. The amount of deflection also depends on the size of the carton and its material properties.
- Vacuum effects. At higher production speeds vacuum effects are more significant and generate an increased resistance to opening.

2.2 Machine-material interactions occurring during bag production

The practical investigation of the form-fill and seal machine revealed unsurprisingly that the critical interactions occur as the material passes over the forming shoulder, figure 2 (2). It also showed that the pre-tension in the web transport system also has to be matched to the shoulder in order to avoid fluctuations from low tension to high tension. In particular, the following factors were identified in order for successful interaction:

- The geometry of the shoulder has to take the form of a developable surface. Deviations from this ideal geometry forced the material to compensate by stretching.
- The frictional forces need to be overcome and this can result in high stresses in the material which may ultimately lead to stretching and even tearing.
- The elimination of bending and buckling of the film as it passed over the leading edge of the forming shoulder.

3.0 Modelling machine-material interaction

A methodology for investigating and modelling machine-material interaction has been generated from a large number of industrial cases. Using these cases it is possible to describe the general activities involved in the creation of representative models of machine-material interaction and ultimately the entire system. In particular, the system can be considered to constitute the packaging process, a range of settings and a set of inputs. These are shown in figure 3. When considering the process; the machine, the material and their interactions are considered and the critical ones identified. The process of determining these interactions is discussed in the previous section.

For the purpose of modelling the complete process, three elements typically need to be considered and are normally defined parametrically. Firstly, the machine system is modelled. This might involve a kinematic simulation of the machine system such as that commonly undertaken to investigate the performance capabilities of the physical system [4]. In order to represent the interactions, models of the behaviour of the material during processing need to be constructed. This frequently involves the consideration of energy and in particular friction, bending and deformation. It may involve the use of techniques such as finite element analysis or the symbolic computation of a set of representative equations and models. In addition to this, it is also necessary to construct accurate models of the geometry and motion of the tooling. This is particularly important where complex forms are considered and where large relative motions occur between the material and the tooling.

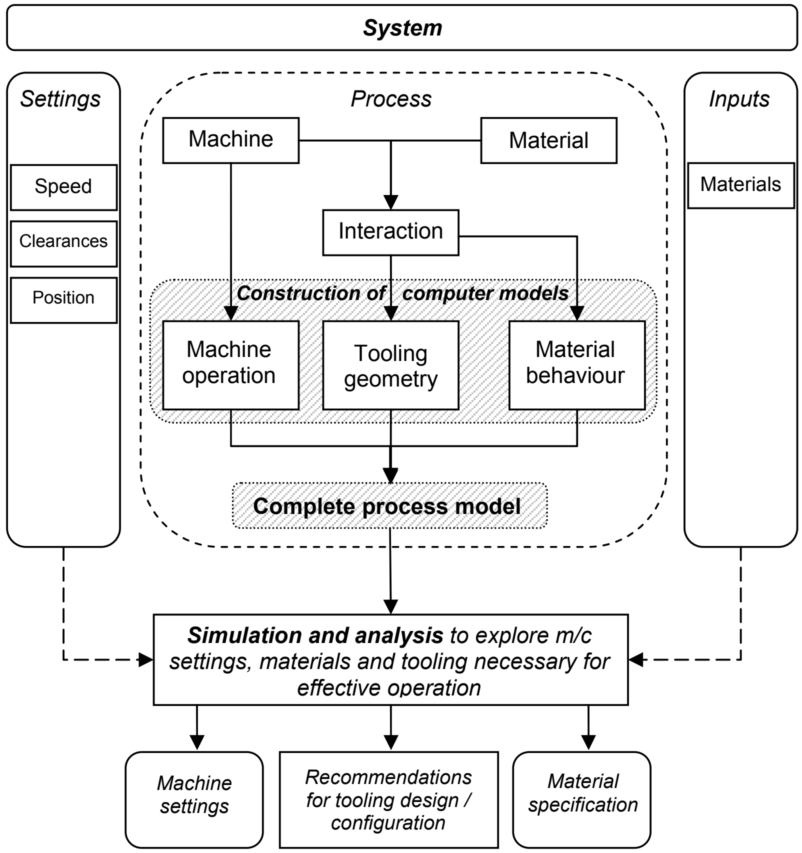

Figure 3 The modelling of machine-material interactions and complete packaging system

Once the three components of the model have been constructed there is a need to combine them or consider them collectively. This can be achieved by incorporating the various parametric models into a single environment or by manually manipulating related parameters, such as geometry, velocities and altered material properties. This results in an integrated representation of the entire process where the influence of machine settings can be investigated and the results of changes to the inputs (materials) can be explored. More specifically, the representation enables:

- The impact of machine settings on process performance to be investigated and suitable settings determined for new pack designs and materials. This is particularly important for determining reliable settings for automated servo-driven changeovers, reducing changeover times and in particular run up [7].
- The performance envelope of different tooling designs or configurations to be explored. It also provides the understanding necessary to improve the design of existing tooling, to rationalise the range of available tooling and to match tooling to specific materials.
- Support for the specification (based on quantitative results) of the material properties necessary for successful processing which, certainly in the area of FMCG, was not previously possible.

3.1 Modelling the interactions occurring during carton production

In order to construct an integrated system representation for carton production systems, the ABAQUS finite element modeller has been used. This allows key machine elements and in particular the epicyclic mechanism and the lugged conveyor to be represented and their motion simulated. The model of the material behaviour has been developed from studies of the use of energy based methods to represent the behaviour of packaging material [8, 9]. This has resulted in new test procedures and an approach for representing the changing properties of creased carton board during processing (folding and unfolding). Figure 4 shows the model of the mechanism and the behaviour of the carton during processing. In figure 5 the results of the model for two different production speeds are shown. On the left hand-side the results show the normal opening of the skillet whilst on the right the skillet has not fully opened and has taken up an overall buckling mode.

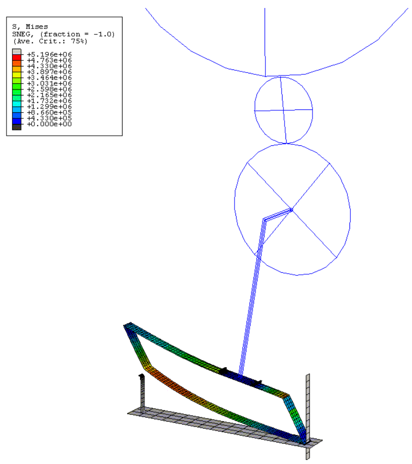

Figure 4 Integrated representation of the machine, material and process.

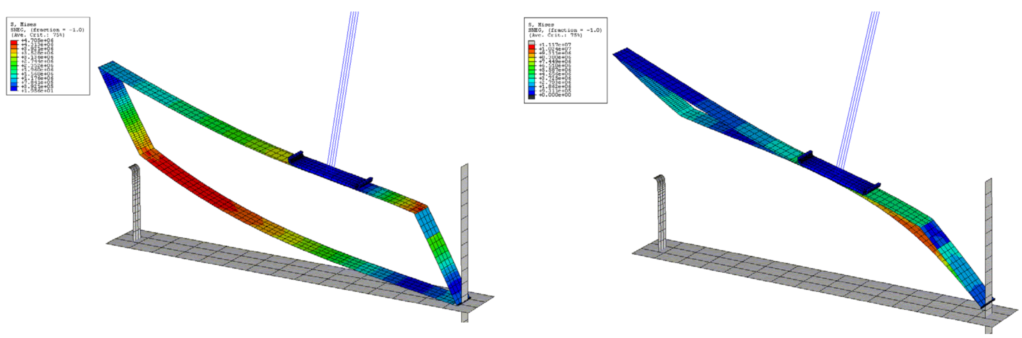

Figure 5 Simulation results for material behaviour at different production speeds

3.2 Modelling the interactions occurring during bag production

In the case of bag production the key material handling elements of the forming shoulder are considered in detail. In particular, a geometric model of the surface has been constructed which allows the full range of different configurations of forming shoulder to be represented. This detailed model of the geometry is critical for providing the data for exploring the behaviour of the material as it passes over the forming shoulder. Figure 6 shows a typical forming shoulder constructed using the traditional fabrication methods and a surface model of it.

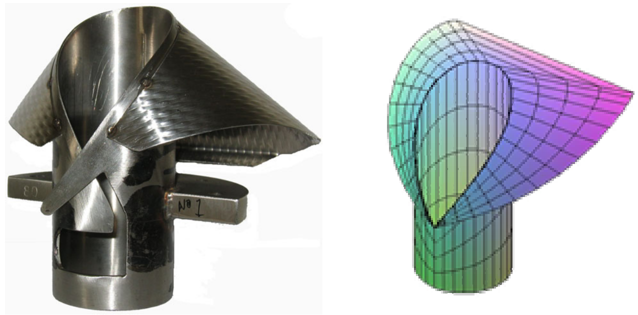

Figure 6 A forming shoulder and a model of its surface

When considering the behaviour of the material and the interactions with the tooling (shoulder) a number of models were created. These included models based on frictional losses and the bending of the film as it passes over the leading edge of the shoulder. The effect of deviations in the surface geometry of the shoulder was also examined. These deviations arise as a consequence of the fabrication process and from wear during use significantly impact on the interaction and in particular the amount of compliance (stretch) in the material necessary to compensate for these deviations.

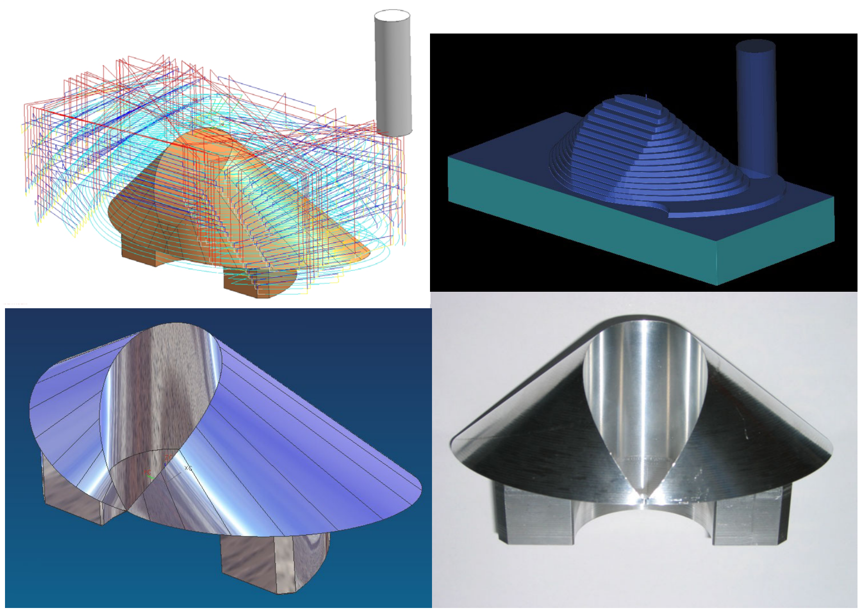

Figure 7 The construction of a solid forming shoulder in UniGraphics

The model of the ideal surface geometry of the shoulder also provides the data necessary for the designs which are CNC machined from solid (figure 7).

4.0 Designing improved tooling

For the two cases considered in this work, the focus of the investigation and modelling is to improve the design of the processes. More specifically, the understanding of the machine-material interactions is used to create tooling designs and settings which are better matched to particular packaging materials. Central to achieving this are the undertaking of modelling episodes for new or changed material properties and pack designs. The use of the integrated representations (previously discussed) for determining tooling design and settings are summarised in the following sections.

4.1 Carton production

In the case of the cartoning machine, the effect of production rates, inclination of the vacuum arm, material properties (stiffness), plim, and crease stiffness were investigated. In particular, the following strategy was adopted to determine the machine settings and tooling set up to maximise process efficacy:

- For a given pack design and material specification, consecutive modelling episodes were performed with increasing production rates. This process was repeated for different angles of inclination of the vacuum arm (tooling). The results of the modelling identified the performance envelope of the system for the material. This could then be used to identify suitable settings which fall within the envelope and also allow for the normal levels of variance expected in material properties.
- The aforementioned process can be repeated for different pack sizes to generate a series of settings for the machine and process. These can be used to provide the data necessary to program the settings for automated servo-driven setup.

In addition to the design of the tooling, the integrated representation was also used to reverse engineer the pack design and provide a specification for the materials which maximises process capability. Once again successive simulations with increasing production rates are performed. Only this time the material properties and crease properties are varied. This again provides the data necessary to represent the relationship between speed, material stiffness and crease stiffness, thereby allowing FMCG manufacturers, machinery manufacturers and material suppliers to specify an optimum packaging system.

4.2 Bag production

For the case of the production of bags, the relationship between the material and the forming shoulder design was investigated in detail. In particular, the induced forces and stresses in the material were considered. For a given material with a known tensile strength and coefficient of friction, it was possible to determine a design of forming shoulder where the forces (and hence stresses in the material) necessary to draw material over the forming shoulder fell below a value derived from the material’s tensile strength. In this manner, the design of the forming shoulder could be matched to the material. The modelling work has also established a computer based model of the critical geometry of the forming shoulder. This provides the design data for the construction of CNC machined tooling. This is central to achieving repeatable and reliable manufacture of tooling which is right first time, thereby saving considerable commissioning time and the need to manufacture and fine tune a large number of forming shoulders.

5.0 Conclusions

This paper has presented the need for machinery manufactures to understand machine-material interaction. This is particularly important given the continually increasing requirements of the customer, the major advances in materials and widespread use of thinner lighter-weight materials, and the worldwide distribution of customers. The last of these makes the commissioning, and trial and error design approaches employed by many organisations difficult to sustain in the long term.

To address this, the work reported deals with understanding and modelling the machine-material interactions occurring during two common packaging operations. Through practical studies the interactions are investigated and then modelled. The modelling involves the construction of an overall process model, which includes component models for the machine, the behaviour of the material and the geometry of the tooling. In this manner, the effect of changes in system settings, tooling design, material properties and pack design on process capabilities can be investigated. By performing successive modelling episodes and varying individual parameters, it is possible to determine the process settings, tooling configurations and material properties necessary to achieve desired production capabilities.

For the two cases considered, the overall process models were used to support the design of tooling and the determination of process settings that maximise process capability and efficiency for one or more given materials. In one case the model also provides the data necessary for the automatic generation of the tooling by CNC machining. This enables the manufacturer not only to better match materials to tooling but also to produce reliable and repeatable tooling to an accurate specification. In addition to this, the models can also provide the data necessary for the matching of materials to existing tooling already used by FMCG producers, and the machine settings necessary for automated servo-driven change over.

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