Omejitve, ki vplivajo na konstrukcijo stebla z ramenom in uporaba natančne geometrije

Constraints Influencing the Design of Forming Shoulders and the Use of Exact Geometry

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Prispevek obravnava konstrukcijo stebla z rokavom pokončne naprave za oblikovanje, polnjenje in zapiranje embalaže. Kakor pri večini strojev za embaliranje, je tudi tu konstrukcija doživela vrsto popravkov in temelji na mnogih izkustvenih pravilih, ki jih je težko in drago uveljaviti naprej. Da bi zmanjšali ta vpliv, poskušamo s tem prispevkom raziskati medsebojna vpliva stroj - material in kako sama konstrukcija vpliva na to. Obravnavana in najbolj vplivna je geometrijska oblika ramena, katere zahtevna narava definiranja je v razpravi, skupaj s konstrukcijskimi izvedbami, ki vplivajo na učinkovitost stroja v pomenu napetosti folije in možnosti pravilnega vodenja. V industrijski praksi se raje spremeni geometrijsko obliko tako, da je vodenje boljše, čeprav se s tem poveča napetost v plašču. Eksperimentalne ugotovitve z natančnimi rameni so pokazale, da imajo boljše vodenje od običajnih in da lahko delujejo s širšim razponom materialov. Ugotovili smo tudi, da je mogoč drugačen način konstrukcije ramena, in sicer z začetno usmeritvijo na napetost plašča namesto na vodenje. Ker natančen rokav pokriva širši razpon materialov, je bilo ugotovljeno tudi, da je mogoče konstruirati stroje z manjšim številom delov.
(Ključne besede: CAD, modeliranje izdelkov, stroji za embaliranje, geometrijske oblike)

This paper considers the design of the forming shoulder, which is a crucial part of a vertical form, fill and seal machine used for packing small discrete items. As with other forms of packaging machine, the basic design has evolved over a number of years and is based on a number of empirical design rules, whose application can be time consuming and costly. To address this issue, the aim of this paper is to investigate the effects of machine-material interaction and the parameters of the design that influence these effects. In particular, the geometry of the shoulder is considered and means for defining its complex form discussed, together with the design issues related to the performance of the machine in terms of web tension and its ability to track correctly. In industrial practice, a modified form of the geometry is used to encourage better tracking, even though this increases web tension. An experimental investigation with exact shoulders has shown that they have better tracking properties than conventional ones and that they can deal successfully with a wider range of materials. It has also been found that a different approach to the design of the shoulder is possible, concentrating initially on web tension rather than tracking. As an exact shoulder can handle a wider range of materials, it is also found that it is possible to design machines in which fewer change parts are required.
(Keywords: computer aided design, product modeling, form-fill-seal machines, forming shoulders)

0 INTRODUCTION

The production of packaging machinery is a highly competitive global market driven by the ever-increasing demands of customers and legislation ([1] and [2]). In 2000, American exports of packaging machinery were valued at just under $5 billion [3]. Packaging manufacturers continue to try to improve the performance of their machines with the aim of increasing the production capabilities, improving reliability and reducing down time and production costs [1]. To do this

successfully it is important not only to improve the machines themselves, but also to understand the interaction between the packaging materials and the machines [2]. Recent legislation, such as the European Packaging Waste Directive, aims to reduce the amount of material being used in packaging. This means that the producers of Fast Moving Consumer Goods (FMCG) are trying to use thinner, lighter weight and recycled packaging materials to take their products to the consumer. The changing specification of materials and the need to meet new requirements puts additional pressure on machinery manufacturers to update their machines.

The underlying design principles of many packaging machines are the result of incremental improvements over the years [4]. In many sectors of the industry, designers lack the fundamental understanding of the process and, of increasing importance, is an understanding of the machine-material interface, which more often than not dictates the performance capabilities of the machine. In today's competitive environment mathematical modelling and simulation are the preferred choice for the design of processes and machine systems rather than the trial-and-error methods still used in some sectors of the industry.

This paper considers a particularly complex production process, i.e., the vertical form, fill and seal machine ([5] and [6]). An example is shown in Figure 1. This is used for the creation of bags or pouches from a reel of packaging material. Such a process is commonly used to package food items like confectionary, biscuits, and snacks ([7] to [9]), and disposable medical devices [10]. It is also possible to use the machines to packages liquids [11].

The material for a vertical form, fill and seal machine is usually supplied as a flat, pre-printed sheet of uniform width and stored on a roll. Figure 1 shows a vertical form, fill and seal machine, and Figure 2 shows a schematic view of the machine illustrating how the film or paper is taken from a roll and bags produced.

A single web of material is drawn from the roll and fed over a forming shoulder that guides the material from the flat into a cylindrical shape around the product feed tube. The action of forming the cylinder brings the edges of the film together. They are either over-lapped so that the opposite sides of the film meet producing a lap seal, or the internal sides of the film are brought together to form a fin seal. The seal itself is usually produced by applying heat and pressure.
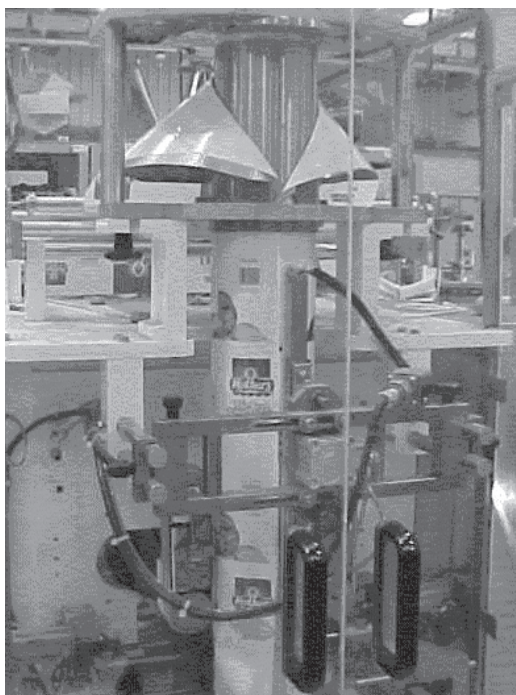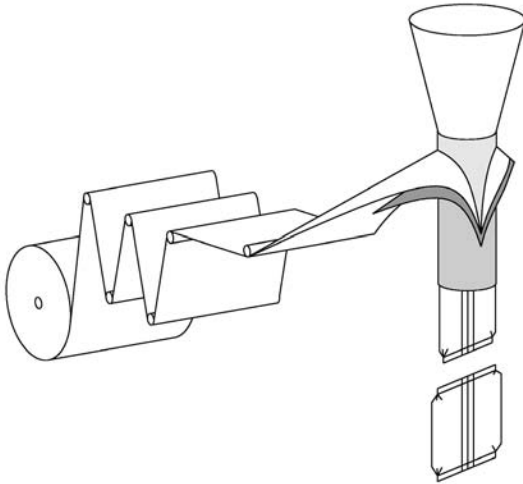

Fig. 1. *Vertical form, fill and seal machine*

Fig. 2. *Schematic of the use of a forming shoulder*

Fig. 3. *Examples of forming shoulders*

The process has now created a tube into which the product is dropped in measured quantities. The packaging material is then cross-sealed and cut to form the complete bag. The action of making this final seal also forms the bottom seal of the next bag. This approach can be adapted to produce a variety of different packs, including packs with flat bottoms and tetrahedral tea bags [1].

In the final stages of formation, the bag is formed around a tube. Often, this is of circular cross-section. Some attention has been given to the cases in which the cross-section takes other forms ([12] to [14]). However, little work has been undertaken which investigates the impact of changes in geometry on the performance of the shoulder and its interaction with a given material, although a historical overview of how materials have evolved over the last half century is available [15].

A number of problems are recognised with vertical form, fill and seal machines. The chief of these is concerned with tracking. This is the ability of the film to pass over the forming shoulder without moving off to one side (or oscillating). Poor tracking results in malformed bags and, in extreme cases, in the film jamming in the machine. It is usually thought that increasing the tension in the web of material improves the ability to track properly. However, excessive tension leads to another problem, which is stretch, or even tearing, of the material. The third problem is creasing or other distortion of the web as it passes over the shoulder.

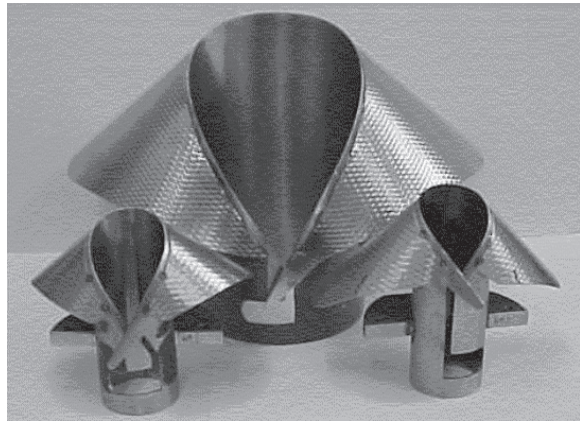The aim of this paper is to investigate the effects of machine-material interaction and the parameters of the design that influence these. There are three areas where the machine and material interact: the feed system where the film leaves the roll, the passages over the forming shoulder, and the traction system below the shoulder which pulls the material through. Each acts to increase the web tension. The one that seems to have the largest effect is the shoulder and it is the design of this that is considered in this paper. Some typical shoulders are shown in Figure 3.

A small number of authors ([16] to [18]) have attempted to represent the geometry of the forming shoulder. The details of such a representation are considered in Section 1. This leads to the parametric model for the geometry that is used here.

The model can be combined with search and bound techniques to investigate the feasible performance envelope for the full range of changes in the design variables of the forming shoulder. This is discussed in Section 2.

The results of this investigation are considered in conjunction with an experimental study into material flow over forming shoulders. The resulting design rules help to provide a more fundamental understanding of the relationships between the design parameters of the forming shoulder, its performance capabilities and the properties of the material.

Factors such as compliance, stiffness and surface friction are particularly important. These properties determine the force necessary to draw the material over the shoulder. If this known, it can be compared with the maximum loading that the material can accommodate before it distorts or fails.

In order to relate these factors to the theoretical investigation, it is necessary to understand the relationship between the shoulder design, tracking and loading. Through experimental studies, given in Section 3, it is shown that the force required to draw the material over the shoulder can increase by 100% for a corresponding decrease in height:radius ratio by a factor of two. Similarly, the ability to control the tracking improves as the height:radius ratio decreases. These practical findings can be combined with the results of the theoretical modelling to generate a set of design rules and a more robust design method for conventional shoulders. These design rules help to provide a more fundamental understanding of the relationships between the design parameters of the forming shoulder, its performance capabilities and the properties of the material.

In particular, what has been found is that the use of shoulders where the geometry is exactly that prescribed by the model tends to result in improved tracking properties. Section 4 gives details of this. What this means is that when a shoulder is designed for a new material there is less need to concentrate upon the tracking aspects. This is discussed in Section 5. The significance of this is that it suggests a different approach to the design of forming shoulders to handle given materials. It means that, initially, tracking can be ignored and instead

attention can be focused on the issue of tension and keeping this as low as possible.

1 MODEL OF THE FORMING SHOULDER

Typical forming shoulders are shown in Figure 3, and Figure 4 shows the basic geometry. This comprises the tube (Figure 4(c)) and the collar (Figure 4(d)). The geometry is to a certain extent specified by that of the bag to be produced. For example, the tube of the forming shoulder must have a circumference equal to twice the width of the bag.

The main determining factor for the geometry of the shoulder is the bending curve. This forms the edge over which the film passes. The bending curve can be regarded as a planar curve of (roughly) parabolic shape, as shown in part (a) of Figure 4.

The vertical tube can be thought of as being formed by wrapping the part below the curve into a circular cylinder. Similarly, if the part above the planar bending curve is wrapped around, then it forms the collar surface. The assembly of these two pieces is shown in Figure 4(b).

With a vertical form, fill and seal machine the material is fed from a roll. This means that it starts as a plane and so there needs to be a smooth transition between the flat plane and the curved
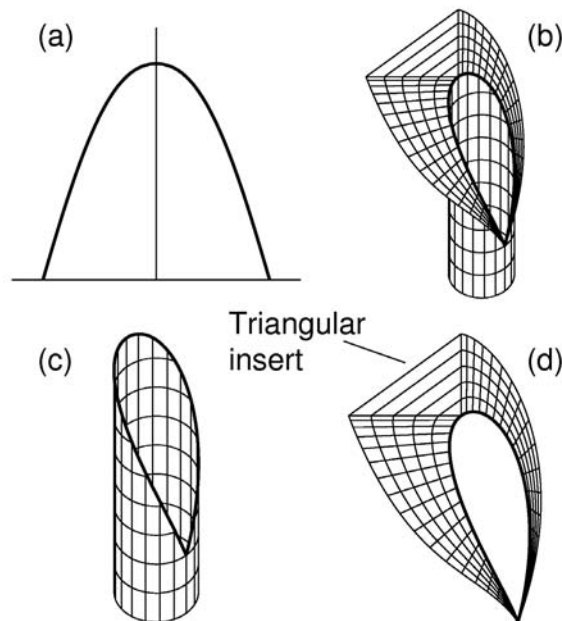

Fig. 4. *Bending curve and shoulder*

collar. To achieve this, a triangular planar surface is usually inserted into the collar surface at its highest point. This is shown in Figure 4(d).

The geometry of the collar surface is complex and there are many constraints upon it. It is important to be able to describe its shape by some form of geometric model.

A model based on two conic surfaces separated by a planar triangle can be used [18]. The bending curve can be taken as the intersection of the surface with a circular cylinder. In this way a collar surface containing a triangular planar insert at its highest point can be created directly.

Although this approach is workable, the resulting set of shoulders that can be used in practice is somewhat limited. There are more versatile approaches available that depend upon initially selecting suitable bending curves in their planar form ([16] and [17]). It is this latter approach that is discussed here.

It is clearly important that the material should not wrinkle, stretch or tear as it passes over the shoulder. This means that the collar surface must be isometric to a plane. Thus the collar needs to be a developable surface ([19] and [20]). Such a surface is formed from a collection of straight-line generators.

As noted in [16], it follows from a result in differential geometry [19], that for a given bending curve wrapped around a cylinder, there are two developable surfaces that contain the curve. One of these is the cylinder itself and the other can be used to define the collar.

Suppose that κ is the curvature of the bending curve when wrapped around the cylinder and that $\bar{\kappa}$ is the curvature of the corresponding planar curve. It is clear that $\bar{\kappa}$ is smaller than κ. Let θ denote the angle between the surface normal to the cylinder and the collar at a typical point on the bending curve. This is also the angle between the tangent planes to the two surfaces. Then, as in [16], this angle is related to the curvature as follows:

$$\cos \theta = 1 - 2 (\bar{\kappa}/\kappa)^2$$

If $z(v)=0$ is the equation of the planar bending curve (for $-\pi R \leq v \leq \pi R$, where R is the radius of the tube), then the curvatures can be found [16] and the above relation can be expressed as follows:

$$\cos \theta = - (R^2 z_{vv} - z_v^2 - 1) / (R^2 + z_v^2 + 1) \quad (1),$$

where the subscript v denotes partial differentiation with respect to v.

If extended sufficiently, the collar surface has an edge of regression along which it turns back on itself. Such a singularity needs to be avoided on that portion of the surface used for the collar itself. It is normally arranged so that the edge of regression lies within the region occupied by the circular cylinder. From [16], the condition for this is the following:

$$R^3 z_{vvv} + R z_v < 0 \quad (2).$$

Straight-line generators that emanate from the bending curve form the collar surface. Provided the curve is smooth, the generators emanate at smoothly varying angles and the surface is well formed and continuous. However, it turns out that if the curve has a discontinuity at its highest point, then the generators on either side are in different directions and a planar triangle can be inserted into the collar. Suppose that the bending curve $z(v)$ in its planar version is an even function so that $z(-v) = z(v)$ and the surface has symmetry. The required discontinuity is in the third derivative of z at $v=0$, the derivative being continuous everywhere else [16].

Suppose that β is the angle between the generators at the highest point of the bending curve. Then this is also the angle at the apex of the inserted triangle. The following expression determines β, where it is assumed that the sign convention and choice of bending curve is such that $z_{vvv}(0+)$ is negative:

$$\tan(\beta/2) = - (2R^2 z_{vvv}(0+) / (R^2 z_{vv}^2 + 1) \quad (3).$$

A purely parabolic bending curve does not allow sufficient freedom to obtain the required discontinuity. So a modified curve is used [16], which is as follows:

$$z = R f(\xi)$$

where:

$$\xi = v / R \text{ for } -\pi \leq \xi \leq \pi$$

and $f(\xi)$ is the even function given by:

$$f(\xi) = c_0 + c_2 \xi^2 + c_3 \xi^3 + c_4 [\cos \xi - 1 + \xi^2/2] + c_5 [\sin \xi - \xi + \xi^3/6] \text{ for } \xi \geq 0 \quad (4).$$
$$f(\xi) = f(-\xi) \text{ for } \xi < 0$$

Four main design parameters can be identified. These are shown in Figure 5, and are discussed below.

h/R is the ratio of the height h of the wrapped bending curve to the radius R of the cylindrical tube.

θ_0 is the back angle, which is the angle between the tangent plane of the shoulder surface and that of the cylinder at the highest point of the bending curve (equivalent to the angle between the normal to the surface and the normal to the tube).

θ_1 is the front angle, which is similar to the angle between the tangent planes of the surface and the tube at the lowest point of the bending curve.

β is the opening angle, which is the angle at the apex of the triangular insert.

There are restrictions on the choices for the coefficients in Equation (4). The first of these are the end conditions at $\xi = 0$ and $\xi = \pi$.

$$h/R = c_0 \qquad (5)$$

$$0 = c_0 + c_2\pi^2 + c_3\pi^3 + c_4(-2 + \pi^2/2) + c_5(-\pi + \pi^3/6) \qquad (6).$$

If Equation (1) is applied to determine the back angle θ_0, then the following equation for coefficient c_2 results.

$$c_2 = -(1/2)\tan(\theta_0/2) \qquad (7).$$

Similarly, Equation (3) relates the coefficients to the opening angle β.

$$\tan(\beta/2) = -12c_3 / (4c_2^2 + 1) \qquad (8).$$

The relation between the coefficients and the front angle θ_1 is obtained from applying Equation (1) at the lowest point of the bending curve.

$$(f''(\xi))^2 = [(f'(\pi))^2 + 1]\tan^2(\theta_1/2) \qquad (9).$$

Additional relations also apply. The first two of these ensure that the planar bending curve has its turning point at $\xi = 0$ and is concave downwards.

$$f'(\xi) = 0 \text{ and } f''(\xi) < 0 \text{ for } 0 \le \xi \le \pi \quad (10).$$

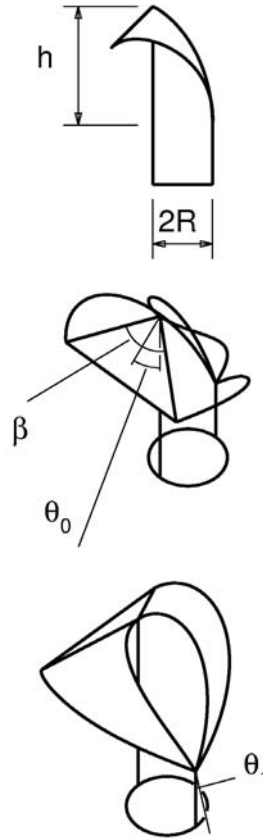A third relation follows from Inequality (2), which is the condition that there are no singularities

Fig. 5. *Parameters of a shoulder*

in the collar surface.

$$f''''(\xi) + f''() < 0 \text{ for } 0 \le \xi \le \pi \qquad (11).$$

For the given form of the bending curve, the left-hand side of this inequality is linear in ξ since the trigonometric terms involved in Equation (4) cancel out.

$$f''''(\xi) + f''(\xi) = (2c_2 + c_4) + (6c_3 + c_5)\xi \qquad (12).$$

Hence, Inequality (11) holds for the whole bending curve if and only if it holds at both $\xi = 0$ and $\xi = \pi$.

The method for finding a bending curve, given the four design parameters, is to start with Equations (5), (7), and (8) and determine c_0, c_2 and c_3. Equations (6) and (9) lead to a quadratic equation for c_4, which leads in turn to two values for c_4 and hence two values for c_5. Of these pairs of values, only one satisfies Relation (10) for $\xi = \pi$. Once the coefficients have been established,

Relations (10) and (11) need to be checked over the entire curve.

These additional inequality constraints mean that some configurations of design parameters generate coefficients that are not acceptable. Thus the class of shoulders that can be generated is restricted. It is beneficial at the design stage to have some understanding of what these restrictions are.

2 DESIGN LIMITATIONS

What emerges from studying industrial practice for designing forming shoulders is that there are several constraints involved. These limit what can be achieved.

The constraints fall into two classes. One class emerges from pure geometric considerations, centred around the shoulder geometry. As discussed in the Section 2, the geometry of the shoulder is critical and needs to be carefully defined to allow material to flow over it easily and without damage. In the design of the shoulder there is a small number of parameters that are at the designers disposal, but these are interrelated and this imposes limits on the designer's choice.

The other class of constraints arises from how the shoulder behaves in use and this involves the question of machine-material interaction. This includes frictional effects, which in turn helps to determine the (minimum) tension required in the web. If the tension is too large then damage to the material and to the shoulder itself may occur. Another important issue is tracking. This is the ability of the material to flow directly and symmetrically over the shoulder and not to veer away to one side. If tracking is poor, then the machine needs to be stopped and reset at frequent intervals and the quality of the packaging can be significantly reduced.

It is clear that the shoulder geometry is very dependent upon the shape of the bending curve. For example, Inequality (11) involves the fourth derivative of the curve. Only slight deviations in the curve due to manufacturing errors or to wear can easily result in this condition being violated. In practice, however, the compliance of the material is sufficient to ensure that some deviations do not have a significant effect, even if a theoretical constraint does not hold. However, this may lead to damage to the material itself.

Some of these limitations on the geometry of the shoulder are investigated in this section; particularly those associated with Relations (10) and (11). More details are given in [21].

The back angle θ_0 is one of the four design parameters. For given values of the other three, there is only a small range of allowable values for θ_0. The graphs in Figure 6 show the lower and upper bounds for θ_0 in a number of cases, in each of which the front angle $_1$ is 10°. The graphs are for different values of the opening angle β. Each gives plots of the lower and upper limits of θ_0 against the height:radius ratio.

The plots show that there is a lower limit for the height:radius ratio, below which a shoulder is not possible. Just above this lower limit, the choices for θ_0 are bounded. The bounds on the interval of choice widen with the ratio and then the interval becomes roughly constant at around 17°.

Figure 7 shows the corresponding graphs for the case when the front angle θ_1 is 30°. These have the same form and again there is a lower limit on the height:radius ratio. This lower limit is slightly higher than in the previous case. However, the most obvious difference is that the curves have moved apart. The lower bound curves have moved significantly to the right and there is a smaller move of the upper bound curves. So there is now a greater choice for the back angle θ_0 for any given value of the height:radius ratio.

The effect that changing the bending curve has on the collar surface is now considered. Shoulders with a front angle θ_1 at 10° and an opening angle β at 90° (a common value in practice) are taken for a number of height:radius ratios. The bending curve is found for each when the back angle θ_0 is at the middle of its allowable range. The value of θ_0 is disturbed by a small amount up to 5° either side of this mid-curve. The largest deviation in the bending curve is identified and plots of these against the change in the back angle are shown in Figure 8. The gradients of these curves provide a measure of the sensitivity of the bending curve to changes in the back angle. The sensitivity increases with the height:radius ratio. Arguing conversely, small changes in the bending curve (which leave it smooth) have the greatest effect on the surface when the height:radius ratio is large.

Now consider the effects of small localised changes to the bending curve. These might arise from wear or damage. In Equality (11) the conditions may become violated and cause the film to distort or buckle. Suppose the bending curve
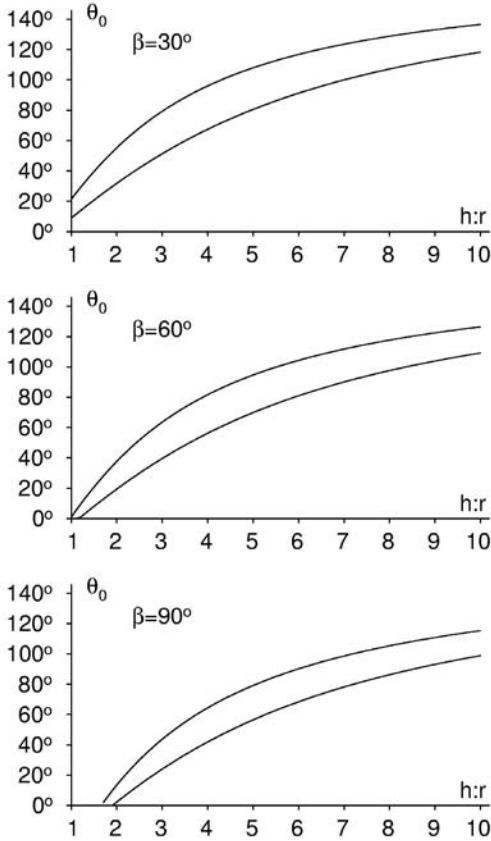
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Fig. 6. *Upper and lower bounds of back angle θ_0 for front angle $\theta_1 = 10°$ and various opening angles β*
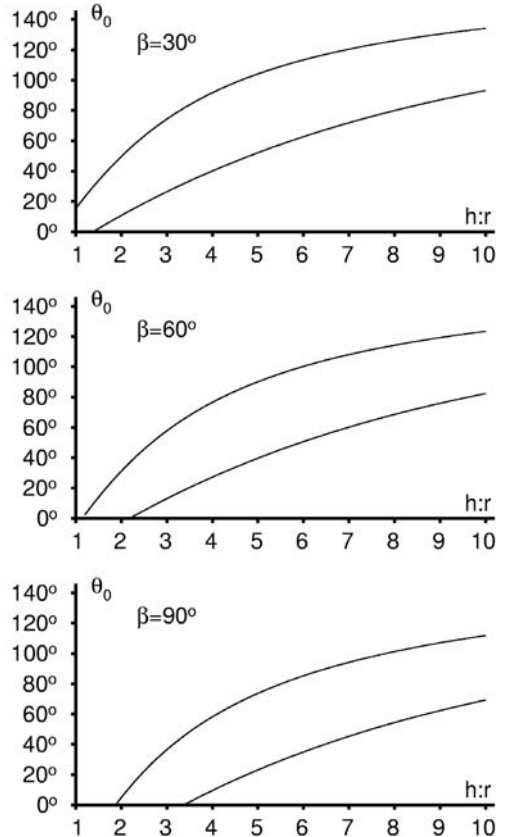

Fig. 7. *Upper and lower bounds of back angle θ_0 for front angle $\theta_1 = 30°$ and various opening angles β*
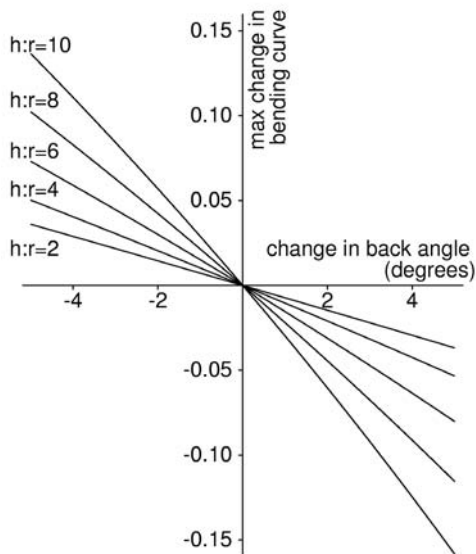

Fig. 8. *Sensitivity of bending curve to changes in back angle θ_0 when $\theta_1 = 10°$ and $\beta = 90°$*

becomes modified from $f(\xi)$ to $f(\xi) + e(\xi)$ where e (which may be zero for most values of ξ). The required inequality is the following:

$$|f''''(\xi) + f''(\xi)| + |e''''(\xi) + e''(\xi)| < 0$$

and using Equation (12) this is the same as:

$$[(2c_2 + c_4) + (6c_3 + c_5)\xi] + |e''''(\xi) + e''(\xi)| < 0$$

Figure 9 shows plots of the first term in square brackets, for ξ between 0° and 180° in a number of cases. These plots are all when the front angle θ_1 is 10° and the opening angle β is 90°. The cases are when the height:radius ratio is 2, 4, 6, 8 and 10, and, for each, the front angle is taken at its lower and upper bounds. It is clear that the value becomes more negative as the ratio increases. This suggests that for higher ratios, small (local) deviations in the bending curve are more likely to be accommodated.
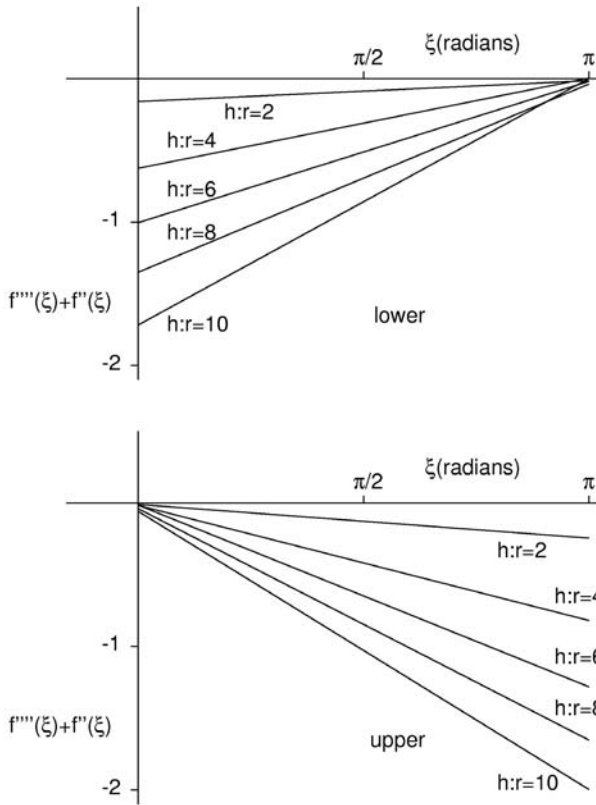
Fig. 9. *Graphs of f ""(ξ) + f "(ξ) for various height:radius ratios and back angles θ₀ with ₁ = 10° and β = 90°*

Fig. 10. *Forces required to pull films over shoulders*

3 PULLING FORCES

As well as the purely geometric properties of a shoulder, its interaction with the packaging material is important. This section discusses the force required to pull material over the shoulder surface. The higher the force that is needed, the more likely that damage occurs to the material.

Experiments have been conducted to investigate the force required to draw material over a range of forming shoulders. Two different films were tested across six forming shoulders. The shoulders were selected to represent the continuum of feasible height:radius ratios for a particular bag width.

To perform the tests, a strip of material was used, whose width was slightly less than the corresponding bag width. This helped in setting up the experiment and took account of the fact that the industrial shoulders used were not designed for precisely the same bag width.
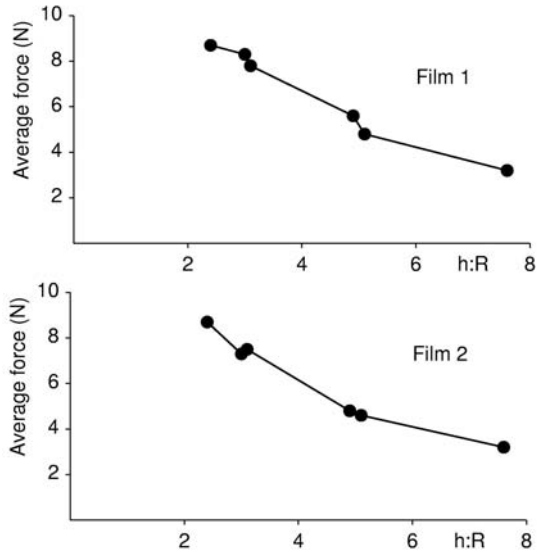
The strip was centred around the highest point of the shoulder and drawn over the shoulder at a constant speed. The free end of the strip was loaded with a range of weights to represent the pre-tension in the web.

The graphs in Figure 10 are for the two films. In fact, the results for both are very similar. What is clear is that the pulling force required is significantly less for shoulders with higher height:radius ratios. As the ratio doubles between 3 and 6, so the force halves from (approximately) 8N to 4N.

This suggests that if a material is susceptible to damage from being stretched, then a shoulder with a high height:radius is required.

4 USE OF EXACT SHOULDERS

Section 1 discusses the geometry of a shoulder that is isomorphic to a plane. Such a

geometry ensures that material can pass over it without wrinkling or stretching. It is common in current industrial practice for a modified form of such a surface to be used. The modification is to reduce slightly the height of the shoulder around the highest point of the bending curve. This is felt to improve the tracking of the film. In particular, it gives the material the ability to self-centre, so if it starts moving asymmetrically then out-of-balance forces encourage it to return to the centre.

The downside of such a modification is that some deformation of the material must occur. Indeed to ensure that the material is in contact with the entire shoulder, including the area of modification, the tension in the material is deliberately increased. This causes it to stretch and so counteract the imprecision in the geometry of the shoulder. The tension is increased by creating a pre-tension in the web by adding weights or springs to the moving rollers in the material feed (to the left in Figure 2) or retardation to the motion of the reel.

To investigate the differences in behaviour between the exact and modified shoulders, a number of exact shoulders were manufactured with dimensions similar to those for some standard modified ones. The exact shoulders can be made by milling from a solid block using machining instructions generated from the geometric model.

Testing revealed that the exact shoulders required significantly less pre-tension to run successfully. As an example, Figure 11 shows results for exact and modified shoulders with a 60° back angle. The bars correspond to three different materials: a metalised film, a polypropylene film, and a paper material that is coated to make it heat

sealable. The unhatched parts of the bars show the minimum pre-tension required to run the material over a modified shoulder. This part is missing for the paper since no pre-tension was found that allowed operation and did not tear the web. In contrast all three materials ran successfully with a pre-tension of 5N, which is the minimum that is allowable under normal operation for the machine used in the tests. This is the single hatched area in the bars. To reduce the pre-tension still further, the material was detached from the input reel and allowed to flow freely into the machine. The shoulder still performed correctly, and tracking was good provided that the web fed in straight. The doubly hatched part of the bars represents the pre-tension of 2N that was estimated for this test.

It is clear that the exact shoulder offers a considerable reduction in the required tension in the web over the form of modified shoulder often used in practice.

It is less clear whether the exact shoulders could experience tracking problems during extended used. No problems were observed during testing. This may be because care was taken to ensure that the feed rollers were correctly aligned with respect to the back of the collar surface. Such an exact set-up is not always possible in an industrial context: for example, the shoulder or related parts may need to be changed from one material to another. However, it seems that the exact shoulder may be more tolerant to variations in the material. So it may be possible to design vertical form, fill and seal machines with a single shoulder to cope with a range of materials. This would eliminate one or more of the major change parts
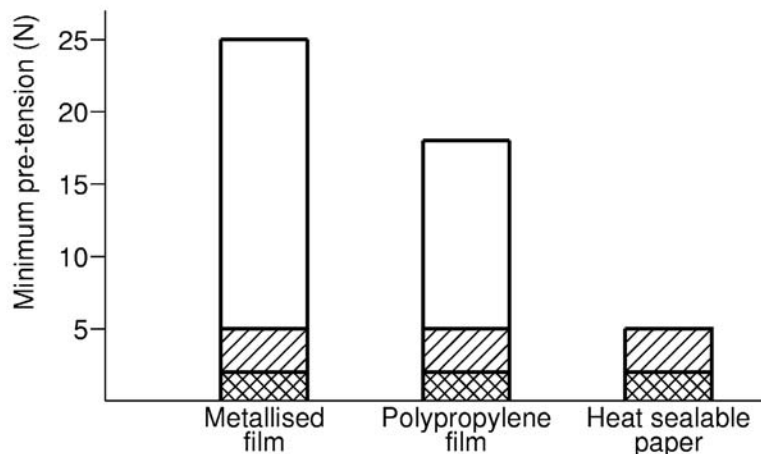

Fig. 11. *Minimum pre-tensions for successful operation*

for this class of machine. If so, care can be taken during manufacture to ensure correct alignment of the rollers and the shoulder.

5 DISCUSSION

A number of design implications can be drawn from the previous work. Four design parameters are identified and the key one is the height:radius ratio. Once this is chosen, strict limitations are imposed upon the values of the other three by the requirements of the geometry. So the following discussion is in terms of this ratio.

In practice, designers often try to use small values for the height:radius ratio. Typical values are around 2 or 3. This ensures that the shoulder itself is more compact. This means that it is easier to manufacture and easier to handle as a change part. The material tension needs to be high simply to pull the web over the shoulder and this may lead to damage to the material. However, a high tension seems to improve tracking during operation.

The graphs in Figures 6 and 7 indicate that a small value for the height:radius ratio means a

low back angle is required and there is a narrow range of choice for it. A low back angle means that the web needs to approach the shoulder from below. However, considered as a whole, the overall machine is compact.

Figure 8 suggests that a low ratio means that there is reduced sensitivity to global errors in the manufacture of the shoulder. The length of the bending curve is low and so there is less opportunity for error in manufacture.

Conversely, consider the case of a high height:radius ratio. Values of 6 or 7 (or greater) occur in practice. This has the advantage of requiring a lower tension in the web and hence less likelihood of damage to it. However, reducing the tension may lead to problems with tracking. A high ratio means the shoulder is less compact and so it is more difficult to manufacture and set up on the machine. The choices for the other design parameters are still bounded, but the interval of choice has widened, giving greater scope to the designer. In particular, the back angle can be chosen to be around 90°, meaning that the web can be fed horizontally to the shoulder, which is more convenient for the operator. In addition, there is less sensitivity to local errors, possibly due to wear; and the wear itself is reduced by the lower web tension.

These considerations are summarised in Figure 12.

The current design practice is to use shoulders with modified geometry to improve tracking. The basic design strategy is to form a compromise between a low web tension to prevent damage to the material and a high tension to guarantee tracking. The critical tension that would cause damage needs to be estimated. This involves some understanding of the frictional forces involved. The smallest height:radius ratio that does not cause a tension in excess of this critical value is often a good choice.

It seems possible that the modified shoulder geometry is used to allow for misalignment in the feed system that comes about through operational use of the machine. Experience with shoulders of the exact geometry suggests that they can be operated successfully with low tensions on a wide range of material types. However, their performance in extended industrial trials still needs to be assessed. These need to investigate questions of tracking and whether the overall machine can be set up so that the intrinsic self-centring of the modified geometry is not required.
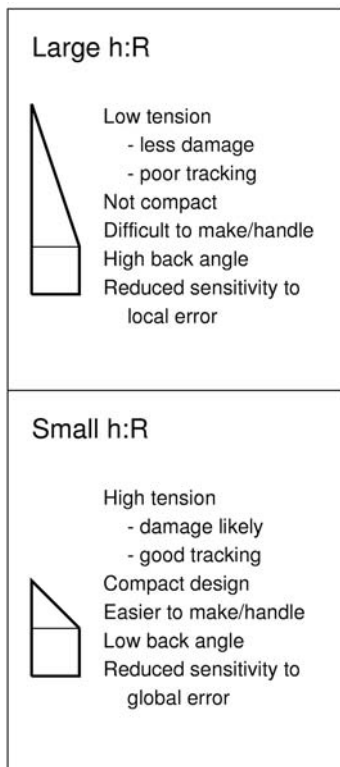

Fig. 12. *Design implications of the choice of height:radius ratio*

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If these questions can be answered positively, then there are two significant implications. The first is a simplified approach to the design of forming shoulders, particularly to the design of shoulders to handle a given film (or range of films). If tracking can be made less of an issue, then there is scope to consider the design initially in terms of obtaining an appropriate (low) tension. This means selecting a suitable height:radius ratio to keep the tension as small as possible (as in Section 4) without making the size unwieldy. The other three parameters for the shoulder are then fairly closely defined by the limitations discussed in Section 3. The second implication is the possibility for using a much reduced range of shoulders (perhaps even a single one) to handle existing ranges of materials. This means that there is less of a requirement to change parts for different production runs, and it reduces the need to design specific shoulders for specific applications.

6 CONCLUSIONS

This paper has considered the effects of machine-material interaction and the parameters of the design that influence these. Issues involved in the design of vertical form, fill and seal machines have been investigated. One of the critical elements is the forming shoulder. Current industrial practice is based on only a limited understanding of the process. This means that often many prototype shoulders have to be designed, tested and modified before a suitable shoulder is configured for the particular application. This process can be time-consuming and costly.

To address some of these issues a mathematical model of the forming shoulder has been examined. This starts with the definition of the bending curve and leads to the construction of the collar surface. This includes a planar triangular region which allows film to be taken from a cylindrical roll.

Four main design parameters have been identified. These are: the height:radius ratio h/R;

the front and back angles θ_0 and θ_1 ; and the opening angle of the triangular insert. The limitations which exist upon these have been discussed. It is noted that very small changes in these parameters may corrupt the good surface definition. In practice the material web may deform to alleviate some of the errors but this is often considered undesirable as it leads to damage to the material.

As well as purely geometric considerations, issues about performance need to be addressed. The force required to pull the web over the shoulder has been considered experimentally and shown to reduce as the height:radius ratio increases.

One of the other practical issues is tracking. To address this, manufacturers often use a modified form of geometry. To compensate for the modification, the web tension needs to be raised, which increases the possibility of damage to the material (and the shoulder). Experimental work with shoulders that have the exact geometry suggests that they can operate over a wider range of material types and with lower tensions. This has implications for the approach used to design shoulders for particular films. Consideration can initially be given to limiting the tension, and effects due to tracking can be considered later on. It also means that it may be possible to use a smaller range of shoulders (perhaps just one) to handle a number of different materials and thus improve the machine design by reducing the amount of change-over required.

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