

**THREE-LAYERED POLYMER COATED STEEL IRONING**  
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**Abstract**

A novel multi-layer polymer coated steel has been developed and is being considered for container applications. This material presents an interesting extension to previous research on polymer laminated steel in ironing, and this paper presents a preliminary evaluation of the new material. A design-of-experiments matrix was prepared using the commercial software package Stat-Ease, and involved varying the die angle, speed, reduction in thickness and tooling temperature. Formability data has been obtained both through experimentation and theoretical modelling with upper bound methods. The three-layered polymer coated steel can result in a material with high ironability.

## 1 INTRODUCTION

Modern food and beverage cans are either two- or three-piece construction. A circular blank is punched from rolled sheet stock, redrawn, ironed in two or three stages, domed, necked, filled and seamed. In between the doming and necking operations, the cans are placed in a wash/coat process which removes the residue lubricants from metal forming (which are invariably toxic in large amounts) and applies a base coating to the metal. The cans are then subjected to one or more spray operations to provide a safe food/drink contact surface and to prevent chemical interactions between container and contents. The polymer also can be applied to the exterior to serve as a permeable coating suitable for further decorating operations. The spray often consists of a polymer resin in a carrier such as methyl ethyl ketone, requiring the carrier fluid to be evaporated, resulting in volatile organic compounds (VOC) which may not be exhausted into the atmosphere but instead must be burned to form more benign products. VOC production is a serious concern of can makers, and has received considerable legislative attention in the past years.

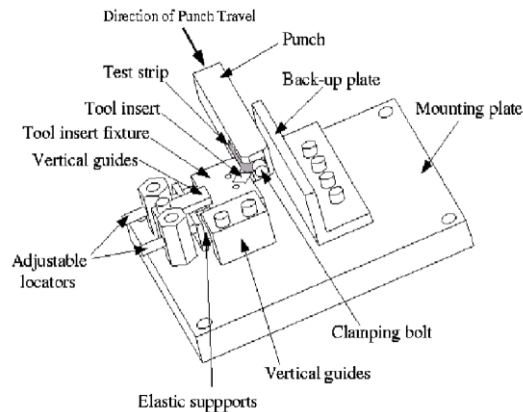
An attractive alternative to the traditional manufacturing process is to use thermoplastic or thermoset laminated rolled steels as base stocks. Such materials consist of pre-heated steel coils that are sandwiched between one or two sheets of polymer. The heated sheets are then immediately quenched, which yields a strong bond between the layers.

It should be noted that the polymers are only useful if they maintain their integrity during forming - any fractures or delamination can cause container corrosion and content spoilage. A cursory review of the metal forming steps in can making results in identification of ironing as the critical operation for polymer coating survivability. In ironing, the pressures are extremely large, the strains and strain rate are very high, and new surface is manufactured from the sheet bulk.

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## 2 PREVIOUS RESEARCH EFFORTS

A strip ironing simulator, shown in Figure 1, was developed for metal forming research at the University of Notre Dame, USA. A workpiece in the form of a sheet-metal strip approximately 25 mm. in width is clamped to a hydraulically-driven punch and pushed through a die opening less than the strip thickness, which directly simulates the ironing process. A 30 hp motor powers a hydraulic pump, so that that ironing speeds of up 2 m/s are possible.



**Figure 1: Schematic illustration of the ironing simulator**

The ironing reduction can be modified by adjusting locator screws. Ironing and normal forces are measured by strain gauges bonded to elastic supports for the tooling fixture, and the thickness of the strip before and after ironing is measured with strip micrometers. A tooling insert can be quickly changed to allow for various materials, die angles and land lengths.

Previous research efforts have been performed using the strip ironing simulator, including work on polymer laminated steels. Jaworski and Schmid [2] demonstrated that laminated polymer-coated sheet steels can be used as ironing stocks. Experiments found that low die angles results in a successful ironing operation, while large die angles result in shaving of the polymer film off of the steel. Kawai et al. [3] and Kenny and Sang [4] also developed an experimental apparatus to measure the friction coefficient on the die surface in the strip ironing process. A metal strip combined with a back-up plate (punch) was pulled through a bearing and a die. Ironing travel, reduction and lubrication were varied to study their effects on the die friction coefficient, surface appearance and galling.

Van der Aa et al. [5] used a finite element model to simulate the wall ironing of polymer coated sheet metal. They verified their results with a plane strip ironing set-up. For those results, they found that a shear deformation occurs in the aluminium sheet metal rather than in the polymer coating, which apparently only reduces in thickness.

Appleby et al. [6] used transparent dies in a plane strain strip drawing apparatus in order to measure die-interface velocities. In this way, incremental displacement boundary conditions were obtained as input in a FEM analysis.

Jaworski et al. [1] investigated the friction and forming characteristics of two steels, one with a tin plate and the other with a chrome plate and polyester laminated coating. Huang and Schmid [7,8] examined the effect of heat in ironing a polymer coated steel workpiece. This research was intended to simulate the proposed use of polymer coated steels without any coolant, and where the tooling temperature is higher than room temperature. Such circumstances arise commonly in ironing, due to the heat dissipated

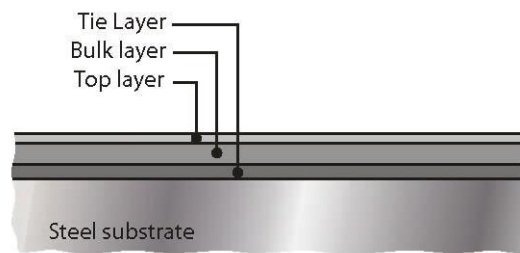
through friction and plastic deformation in the process. They also demonstrated that ironing without a coolant such as water is not likely to be feasible because of the significant reduction in material survivability.

Kampus and Nardin [9] used the theory of plasticity to model the ironing process, making an ironing workability diagram to describe the stress-strain state. They applied this model to production of cups with non-uniform wall thickness, where observed with the help of a FEM software the action of the superimposed forces. The theoretical model and experiments showed that the maximum strain can be increased by up to 40% with the use of a superimposed force.

### 3 MATERIALS

The novel three-layered polymer coating considered in this research is illustrated in Figure 2, and has the following characteristics:

- A three-layer system can be placed on both the punch and die sides of the sheet.
- The layer bonded to the metal substrate is referred to as the Tie layer, followed by the Bulk layer and finally the Top layer. A typical thickness ratio for the tie/bulk/top layers is 1:3:1, with typical overall thickness of 12.5-25  $\mu\text{m}$ .
- The layers can be adjusted to meet specific customer requirements.



**Figure 2: Illustration of the three-layered polymer-coated steel used in the experiments.**

There is significant flexibility in formulating this material, and many combinations of chemical and mechanical properties can be achieved. Two materials were provided for this pilot study, identified as 702 and 705. The polymer system on these materials was the same, but the substrate varied. The substrate for material 702 was 0.223 mm thick, T-4, tin-free steel (TFS), whereas the substrate for material 705 is a 0.211 mm thick, T-4, tin-plated steel. These materials had a visible difference in surface brightness - the tin-plated steel appeared slightly whiter in ambient light.

### 4 EXPERIMENTAL INVESTIGATION

The ironing simulator depicted in Figure 2 was used to evaluate the ironability of both the 702 and 705 materials at room and elevated temperatures.

#### 4.1 TIN-PLATED STEEL SUBSTRATE (705)

The first material tested was the tin-plated steel substrate identified as Material 705. Under no conditions investigated could the 705 material be successfully ironed. Instead, the coating was shaved off of the substrate for all tool geometries and reductions in thickness. The mechanisms and causes of shaving will be discussed below.

## **4.2 TIN-FREE STEEL SUBSTRATE (702)**

Material 702 displayed good ironability for a number of conditions. A design-of-experiments matrix was prepared using the commercial software package Stat-Ease, and involved varying the die angle, speed, reduction in thickness and tooling temperature. Since the experimental matrix on the white side was conducted first, and the effect of opacity was not expected to affect ironability, a reduced experiment matrix was completed on the clear side. Experiments can result in successful ironing or the removal or shaving off of one or more polymer layers.

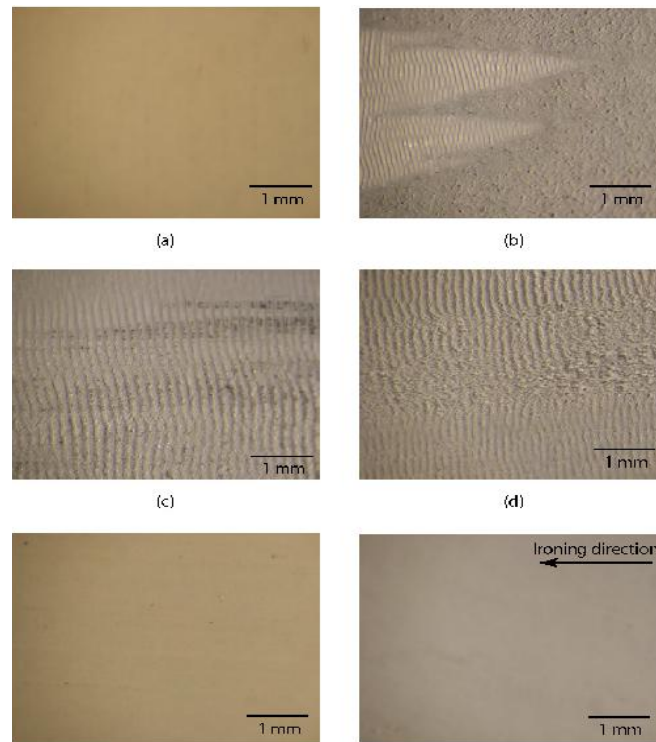
It should be noted that these results are pertinent to the die-workpiece interface; the punch-workpiece interface demonstrated good survivability under all conditions.

A Surface Quality Factor (SQF) was used as a qualitative measure of surface appearance after an experiment. The Surface Quality Factor has been defined as:

0. Shaving of the polymer coating.
2. Partially survived/partially shaved coating; surviving coating displays significant roughening.
4. Coating is partially intact, with local defects and roughening.
8. Intact coating with minor surface defects.
10. Successful ironing; intact coating with superior surface finish.

Representative examples of these Surface Quality Factors are given in Figure 3. It should be noted that shaving (surface quality factor of 0) still involved one or more polymer layers adhering to the steel as described below.

The SQF is a qualitative measure, based on visual appearance of the surface. In general, an SQF of 8 or 10 represents a sample that is acceptable for ironing applications. These polymer coatings maintained their integrity and would satisfy the design requirements of protecting the can wall material and contents from each other. An SQF of 0-4 indicates a surface with serious defects that are clearly unacceptable for functional reasons. While a qualitative measure, it should be noted that there is a clear distinction between the shaved or partially-shaved surfaces (with an SQF of 0-4) and a successfully ironed surface (with an SQF of 8-10). When damage to the polymer surface occurred, it was rarely localized, but instead occurred over the entire specimen surface.



**Figure 4: Representative surface microphotographs of the test specimens. (a) As-received; (b) surface quality factor (SQF)=0; (c) SQF=2; (d) SQF=4; (e) SQF=8; (f) SQF=10.**

Also, the surface quality that is seen in Figure 4 could most likely be improved if the tooling surface finish was improved. The titanium carbide inserts used for ironing did leave noticeable scratches in some specimens. The inserts were produced by diamond polishing, but were not refinished for the subject research in order to save time and expenses; it is felt that surface quality factors of 8 could probably be improved with better tool surface finish.

## 5 THEORETICAL MODELIZATION

Two possible results have been considered as ironing consequence on the workpiece: successful ironing and shaving. In this case, the workpiece is damaged and it's not appropriate. The steel base is coated by three polymer layers, and if the workpiece is damaged in the ironing, one of these consequences will occur:

- Damage only at the top polymer layer.
- Damage at both top and bulk polymer layers.
- Damage at the three polymer layers.

Two models have been developed using the Upper Bound Method: one for successful ironing and the another one in case of shaving. The power needed to damage the tie and bulk layers is always higher than the power needed for produce damage at the top layer. For this reason it has been modelled only the case where it's produced damage at the top layer.

The two corresponding upper bound models developed are characterized by some simplifying assumptions. As discussed above, both the coatings and workpiece are assumed to have no strain hardening or strain rate effects, and sticking frictions and plane

strain conditions are invoked. The materials are considered rigid, perfectly plastic solids with constant shear strengths, which is necessary for deformation to occur in well defined shear planes. But however, a polymer seldom behaves as a perfectly plastic material, nor does it typically deform along discrete planes. However, it is felt that the use of a reasonable amount of deformation planes will improve the accuracy of the power estimates.

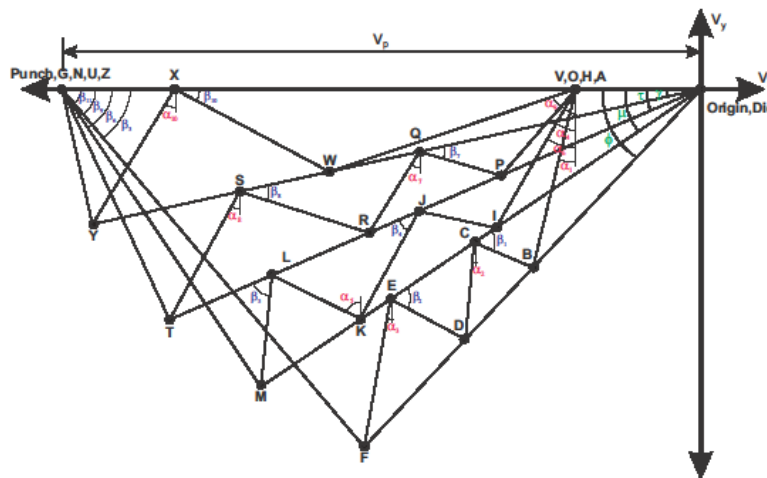
In the models presented, the coating effective shear strength,  $k_i$ , is specified as fraction of the workpiece shear strength,  $k_p$ .

Each frictional interface in the system has a unique friction factor. The workpiece-punch interface is characterized by  $m_1$ , the steel-tie layer interface by  $m_2$ , the tie-bulk layers interface by  $m_3$ , the bulk-top layers interface by  $m_4$ , and finally,  $m_5$  represents the friction in die-top layer interface.

### 5.1 SUCCESSFUL IRONING MODEL

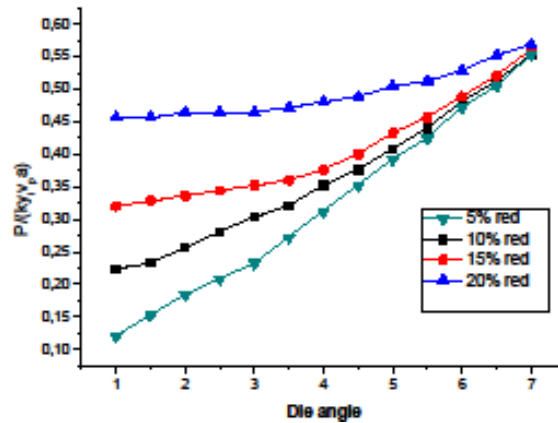
The deformation planes in the polymer layers and workpiece are functions of the variable angles  $\alpha_1$  through  $\alpha_{10}$ , and  $\beta_1$  through  $\beta_5$ , as well as specified values of reduction and of  $\mu$ ,  $\phi$ ,  $\phi$ , and  $\tau$  angles. As can be appreciated, the angles in region borders with the vertical are represented with the  $\alpha$  greek letter. The  $\phi$  angle is the die angle. The angles  $\mu$ ,  $\phi$ , and  $\tau$  are given by the horizontal and every polymer layer.

The angles characterizing the geometry of the velocity discontinuity field are present in the hodograph shown in Figure 5, where all the considered angles can be seen.



**Figure 5: Hodograph for successful ironing condition**

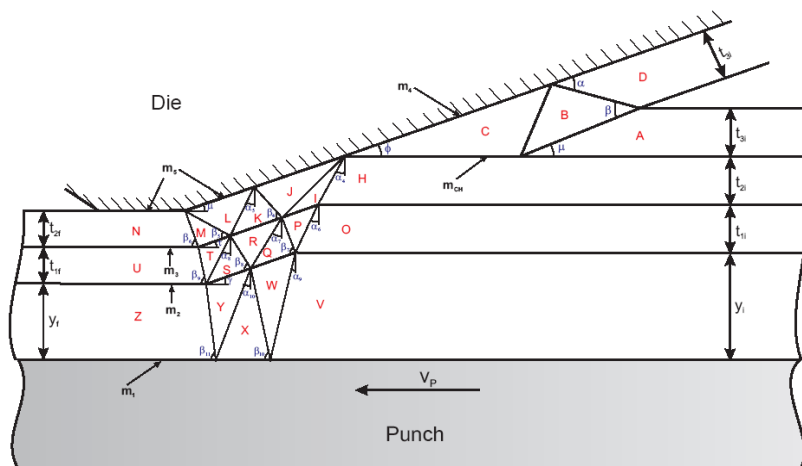
Figure 6 depicts the non-dimensional power curves for the successful ironing model. As can be seen, an increase in reduction requires an increase in power. At the same time, power also increases with die angle.



**Figure 6: Non-dimensional power versus die angle for varying reduction, if successful ironing model is used.**

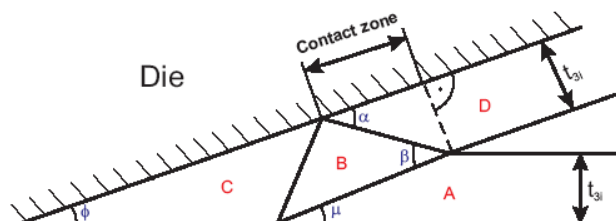
## 5.2 SHAVING MODEL

Figure 7 shows a velocity discontinuity field class for shaving of a three-layer polymer coated steel.



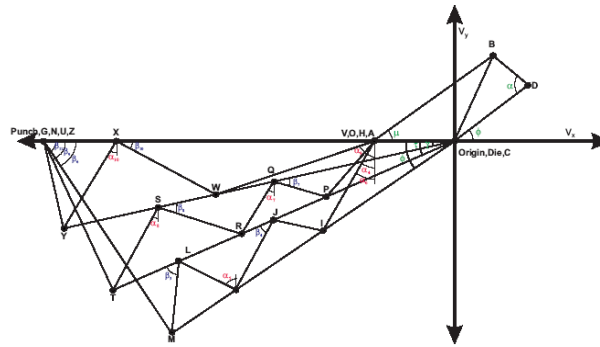
**Figure 7: Velocity discontinuity field for a successful ironing**

Region D is the saved polymer coating, and its final thickness is equal to its initial thickness. The actual area of contact between this layer and the die is difficult to calculate, so an approximation is used. This contact length between D and Die is shown in Figure 8, following an approach used by Wilson and Halliday [10].



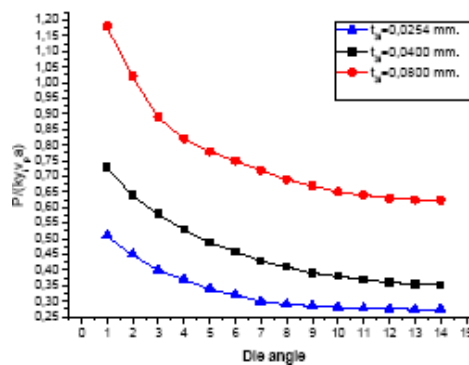
**Figure 8: Polymer-Die contact is assumed to exist over length indicated.**

The resulting velocity hodograph for the shaving condition is shown in Figure 9. It's important to mention that region C is stationary [1].



**Figure 9: Hodograph for shaving condition**

Figure 10 shows the power curves for the shaving model for varying initial coating thickness. An increase in coating thickness increases the dissipated power. However, this power decreases as the die angle becomes larger.



**Figure 10: Non-dimensional power versus die angle for varying coating thickness, if shaving model is used.**

## 6 RESULTS

The surface quality factor is very high at die angles around 6° or lower, but shaving occurs with greater frequency as the die angle increases.

The process parameters were evaluated with respect to their importance on surface quality factor (analysis of variance). The results are summarized in Table 1. As can be seen, the die angle was the most important variable within the range of variables examined. This is consistent with Jaworski and Schmid [2].

**Table 1: Analysis of variance results**

Variable	Clear polymer (sum of squares)	White polymer (sum of squares)
Die angle	59.52	481.59
Ironing speed	5.36	10.75
Reduction in thickness	0.024	13.3
Temperature	0.024	19.4

Speed had a minor effect, with higher speeds leading to better ironability. This is consistent with strain rate effects on polymer properties; in previous tests, a stronger polymer was less likely to shave and more likely to iron properly.



## 7 CONCLUSIONS

Formability data has been obtained both through experimentation and theoretical modelling with upper bound methods. The three-layered polymer coated steel can result in a material with high ironability. Based on the research performed, we conclude:

- The polymer laminate coated steel displayed good formability on the punch side of the ironing operation. This is significant, in that this is the container interior in most ironing operations, and suggests that the concept of using polymer laminated steels as ironing basestocks is a sound strategy for reducing VOC emissions.

- Ironing die angle is the most important manufacturing process variable; with the 702 material, good ironability is encountered at die angles around six degrees and lower. Higher die angles lead to shaving of the polymer coating.

- Ironing speed had a minor effect on ironability, with increased ironability at higher speeds.

- Shaving, when present, usually occurred between the tie layer and bulk layer or the top and the bulk layers at the conditions examined. The tie layer always survived ironing for the conditions examined.

- The behavior of the polymer was unchanged whether the tests were performed at room temperature or at 100°C.

- The two theoretical models allow examining the influence of material parameters, and it's possible to give insight into how to design a material that irons well.

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