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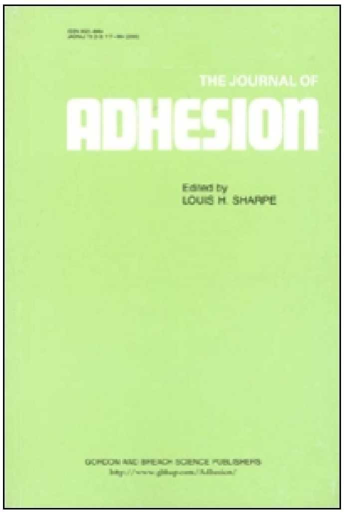

The Journal of Adhesion

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

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To cite this Article Polyakova, A. , Stepanov, E. V. , Provder, T. , Hiltner, A. and Baer, E.(2000) 'Relationship of Coating Failure to Deformation in the Deep Drawn Cup', The Journal of Adhesion, 72: 1, 37 — 50
To link to this Article: DOI: 10.1080/00218460008029266
URL: http://dx.doi.org/10.1080/00218460008029266

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J. Adhesion, 2000, Vol. 72, pp. 37–50
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Relationship of Coating Failure to Deformation in the Deep Drawn Cup

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(Received 18 June 1999; In final form 6 October 1999)

Deformation of the metal substrate in the deep drawing process was characterized by macroscopic appearance and strain distribution. The results of the analysis were correlated with the modes of coating failure. The characteristic ears and valleys at the top of the cup and buckling of the metal in the valley regions resulted from instabilities raised during the cupping process. Earing was a plastic instability that originated from the combined factors of the crystallographic unit cell and the anisotropy of the rolled metal substrate. Buckling was an elastic instability that occurred when the valleys lost constraint before the ears. Stopping the forming process at intermediate positions before the cup was completely formed revealed four stages in the cupping process. Stage I was the initial indentation with formation of six ears. Stage II was conversion from 6 ears to 4 ears separated by alternating deep and shallow valleys. Stage III, loss of constraint in the deep valleys, led to buckling. Stage IV was total loss of constraint. Relationships between the deep drawing process as described by the 4 stages and coating failure were explored with two coating formulations: one that did not fail during deep drawing and one that failed. Two failure modes were observed on the deep drawn cup. Mode I, coating delamination at the top of the cup, was related to the bucking instability. Mode II, loss of adhesion along the cup wall, was caused by elastic retraction of the unconstrained cup in stage IV.

Keywords: Deep drawing; cupping; metal coatings; coating failure; adhesion

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INTRODUCTION

The application of organic coatings on metal containers for protective and decorative purposes has been practiced for a long time. The spectrum of material properties required of high performance coatings includes scratch and chemical resistance, high temperature stability, toughness and flexibility. The coatings are applied to the metal either before or after deformation depending on the forming method. Deep drawing and wall ironing are two modern can-making processes. The amount of metal deformation in the wall ironing process is considerable with substantial insult to the surface during forming. In this process the can body must be coated after fabrication. In deep drawing, the coating is applied to the flat metal sheet before forming. The thin polymer coating must deform with the metal during the drawing procedure. This requires the coating to undergo extensive deformation without tearing, forming holes, or losing adhesion. During the process, the coated metal substrate is subjected to complex axial and shear stresses. The resulting strain distribution determines the stresses on the coating and the ensuing modes of coating failure.

Conventionally, the performance of candidate coatings is tested with a deep drawing apparatus that forms a cylindrical cup from a flat metal blank by means of a cylindrical punch and die set assembled in a power press [1]. The forming operation is intended to mimic the deformation that the coated metal would encounter during can manufacturing. After deep drawing, the coating is visually inspected for failure and qualitative comparison is made with control materials that passed the forming operation without failure.

Various studies have examined the relationship between the chemical composition of formulations similar to those used for coating metal and the properties that might affect performance in the deep drawing process, such as glass transition temperature (T_g), sub-T_g relaxations [2–6], and flexibility [7, 8]. It has also been recognized that adhesion and residual stresses are important features [9, 10], and several methods have been proposed for measuring the adhesion of thin coatings [10–12]. However, no correlations have been made with performance in the deep drawing process. Additional methods are used to evaluate other practical aspects of coating performance such as abrasion resistance, surface lubricity, and heat resistance [13]. Again, empirical tests are relied upon for evaluation of coating performance in the absence of a more fundamental approach.

To design improved coatings that will undergo extensive deformation in the deep drawing process without failure, it is useful to identify the modes of coating failure and, subsequently, to relate the failure modes to the deformation history of the metal substrate and to key properties of the coating material. In this paper, we first characterize the deformation of the uncoated metal substrate in the deep drawing process. Secondly, we determine the failure modes of a thin coating on the metal and, finally, we correlate the coating failure modes to the substrate deformation. A commercial coating and one especially formulated to fail easily are compared.

EXPERIMENTAL

The metal substrate was a 0.2 mm thick tin-coated steel plate supplied by ICI Paints, Strongsville, OH, USA. The rolling direction of the metal plate was identified from the striations on the metal surface. A 10 cm by 10 cm square was placed in an Erichsen cupping machine which cut a circular blank 6.4 cm in diameter and punched the blank into a cylindrical cup. In order to determine the progression of metal deformation during forming, the punch penetration was stopped at various depths and the resulting series of cups was analyzed.

A circular grid was used to determine the strain distribution in the fully-drawn cup. Circles 2 mm in diameter were scratched on metal substrates. Upon deep drawing, the circles were transformed into ellipsoids. The geometrical changes were measured by employing a stereo optical microscope with image analysis. The deep drawn cup was cut along the drawing direction and the thickness was measured by optical microscopy.

Two epoxy coatings were provided by ICI Paints. A commercial, solvent-based, epoxy coating did not fail during forming. A water-based coating, designed to fail easily, was used to determine the modes of coating failure. The metal substrate was cleaned with methyl ethyl ketone before coating application. The epoxy coating was cast on the metal sheet using a #20 coating bar to give a dry film thickness of $\approx 10\,\mu m$. The coated metal sheets were baked in a gas-fired, forced air oven at 210°C for 10 min. The epoxy-coated metal blanks were deep drawn and the coating failure modes were identified. The deep drawing process was stopped at different punch penetration depths and the series of cups was analyzed to obtain the relationship between coating failure and deformation of the metal substrate.

RESULTS AND DISCUSSION

The Deep Drawing Process

The deep drawing process for making cups uses a punch to force a flat circular blank of material into a cylindrical die as shown in Figure 1. The blank is centered on the die and a blank holder pressure is applied. The blank holder pressure is adjusted to prevent wrinkling but to allow the blank to slip easily into the die. The gap width between the die and punch should be larger than the blank thickness to prevent ironing. The gap width used in the present study was about 20 percent greater than the thickness of the blank.

In the deep drawing of a cup, the metal is subjected to blank holder and punch forces. Figure 2 shows these forces and the resultant stresses on a pie-shaped segment of the partially-formed cup. The metal at the center of the blank under the head of the punch wraps

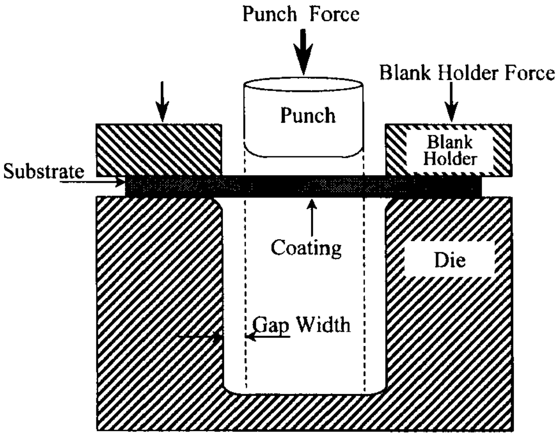

FIGURE 1 Schematic diagram of the deep drawing process.

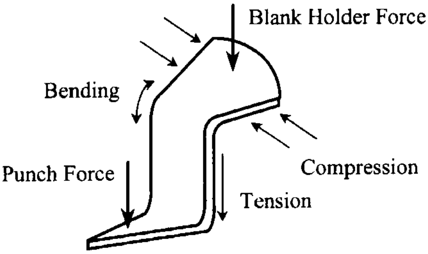

FIGURE 2 Deformation in a pie-shaped section from the drawn cup.

around the punch and experiences minimal stress. As the punch forces the blank into the die, the metal passes over the die curvature where it first bends and then straightens. Once it enters the cup wall, the metal experiences a tensile stress. Concurrently, metal in the outer portion of the blank is drawn inward toward the die. The outer circumference must continuously decrease from that of the original blank to that of the finished cup. The constraint of the blank holder prevents wrinkling; instead, the metal responds to the compressive stress in the circumferential direction with a continual increase in thickness as the blank moves inward.

Description of the Metal Cup

The final product of the deep drawing process is a cylindrical cup. Figure 3 shows a deep drawn cup 22-mm in diameter, formed from a circular blank 44 mm in diameter. The top of the cup is undulating with ear and valley regions. Buckling is usually observed in the valley regions of the deep drawn cups. Edge profiles of two typical cups are presented in Figure 4. Four ears and four valleys appear in the final cup. Two shallow and two deep valleys are distinguished. The positions of the ears and valleys are always the same relative to the rolling direction of the metal. Two pairs of ears at ± 60° and ± 120° are arranged symmetrically with respect to the rolling direction. Shallow valleys centered at 0° and 180° separate the widely spaced ears. Deep valleys at ± 90° separate the closely spaced ears.

Earing and buckling are due to instabilities raised during the cupping process. The earing instability is well known from the literature. A general theory of earing was first proposed by Hill [14]. The origin

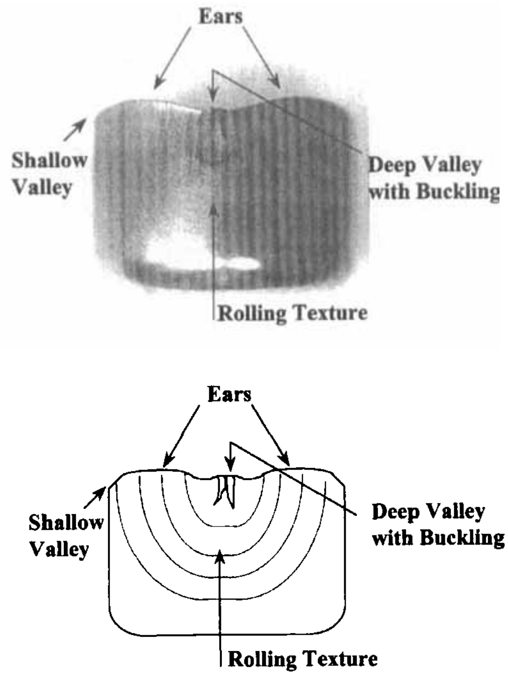

FIGURE 3 Photograph and schematic depiction of a deep drawn metal cup.

of earing lies in the crystallographic unit cell of the metal blank and the planar anisotropy introduced by rolling. The b.c.c. metals used in most can-making processes can generate four, six and sometimes eight ears [15]. The contributions of crystallographic unit cell and planar anisotropy to the final earing profile can be separated using an analytical procedure [16].

In the present deep drawing experiments, six valleys separated by 60° appeared initially due to easier yielding along certain crystallographic planes [17]. However, anisotropy of the metal blank made yielding easier in the rolling direction. This produced two valleys in the rolling direction. As a result of superposition of the crystallographic and planar anisotropy contributions, the initial six-eared cup converted to an asymmetric four-eared cup as deep drawing proceeded. The two ears at 0° and 180° to the rolling direction that originated from the crystallographic unit cell transformed into shallow valleys by

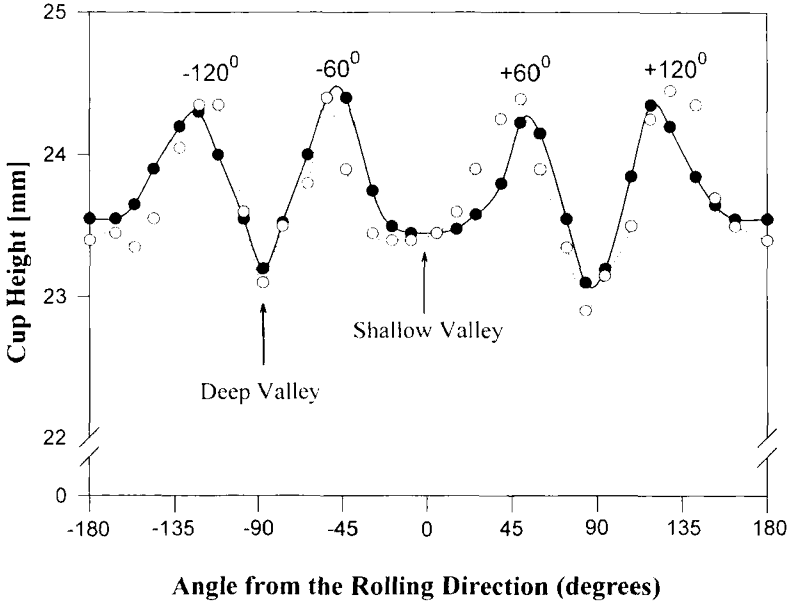

FIGURE 4 Profiles of two deep drawn cups showing the positions of ears and valleys.

superposition of the valleys from the rolling anisotropy. As a result, four ears alternating with deep and shallow valleys finally developed.

Stages of the Deep Drawing Process

The cupping process was stopped at various punch depths, and the appearance of the partially formed cup was analyzed. Four stages of the cupping process were defined as shown in Figure 5. A series of sketches shows side and top views of the initial position of the metal as it deformed during cupping. The metal at the center of the undeformed blank, Figure 5a, wrapped around the profile of the punch as soon as deep drawing was initiated. When the cupping process was stopped at the point of initial punch indentation, stage I, six ears were observed as shown in the top view of Figure 5b. As the blank was drawn further into the die, two of the ears were converted into shallow valleys, stage II. Four ears separated by alternating deep and shallow valleys were observed as shown in Figure 5c.

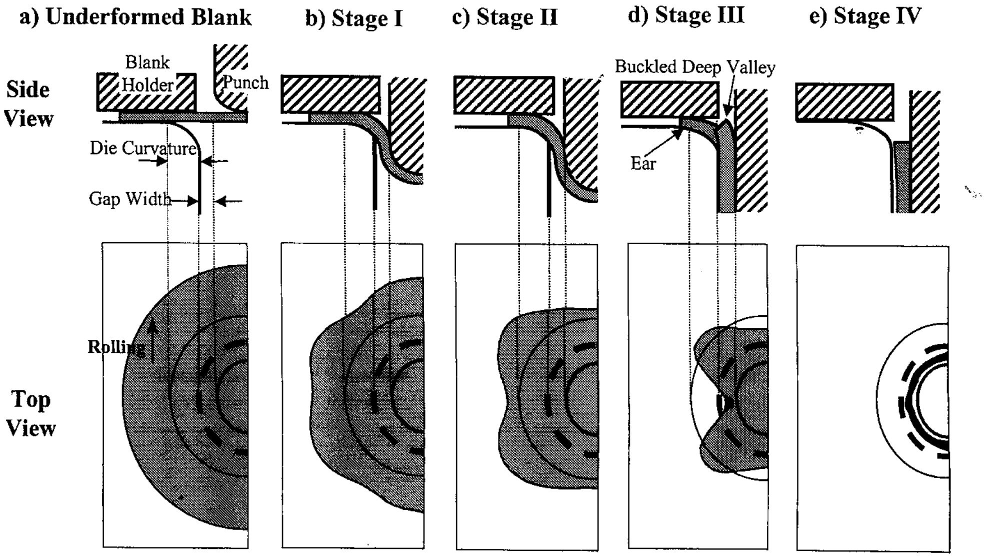

FIGURE 5 Stages of metal deformation in the deep drawing process: (a) The undeformed blank; (b) stage I, initial indentation and formation of 6 ears; (c) stage II, conversion from 6 ears to 4 ears; (d) stage III, partial loss of constraint and buckling instability and (e) stage IV, full draw with complete loss of constraint.

The buckling instability was deeply related to earing. As drawing continued past stage II, the blank lost the constraint of the blank holder in the deep valleys, while the ears and shallow valleys were still constrained, stage III. At this point, the unconstrained valleys were free to buckle. The buckle was forced into a waveform when it entered the gap, Figure 5d. The shallow valleys lost constraint next, and sometimes they also buckled. At the very end of the deep drawing process the entire cup lost constraint, stage IV, and slipped into the gap between the die wall and the punch as shown in Figure 5e.

In summary, the analysis of partially-drawn cups identified four stages of the deep drawing process. Stage I was the initial indentation with formation of six ears. Stage II was conversion from six ears to four ears separated by alternating deep and shallow valleys. Stage III, loss of constraint in the deep valleys, led to buckling. Stage IV was total loss of constraint.

Strain Distribution in the Deep Drawn Cup

Strains on the fully deep drawn cup were measured from a circular grid. During forming, the initial circles were transformed into ellipses, Figure 6. The main axes of the ellipses were always aligned along the principal strain direction. The magnitudes of the strains were calculated from the geometrical changes: radial tensile strain, $\delta_h = (h - d)/d$,

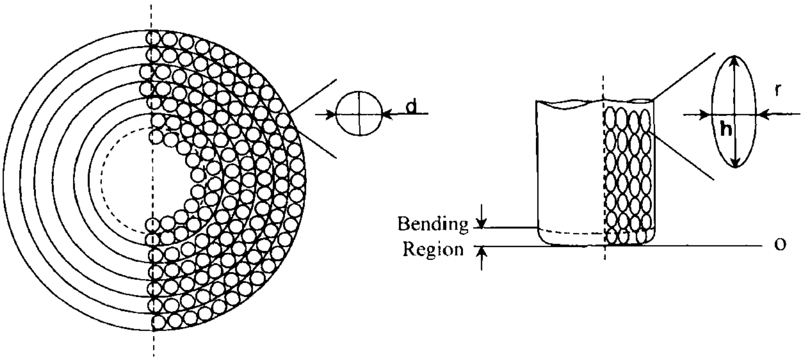

FIGURE 6 Schematic of the circular grid on the undeformed metal and the deep drawn cup used to measure strain distribution.

and circumferential compressive strain, $\delta_r = (d - r)/d$, where d is the initial diameter of the circle, and h and r are the diameters of the ellipsoid in the radial and circumferential directions, respectively. The thickness strain along the cup wall in the ear region was measured by optical microscopy. The volume change was calculated from the three components of strain.

Figure 7 compares the three strain components in the ear and valley regions. The initial 5-mm of the cup height is curved, and is referred to as the bending region. The first 2-mm showed no significant strain; thereafter, all the components of strain increased gradually with cup height. The radial strain was tensile; the circumferential strain was compressive. The compressive circumferential strain increased to a maximum of 40% at the top of the cup. The tensile radial strain was about 40% at the top of the cup. A small difference in the strain magnitude between the valley and ear regions was observed. The magnitudes of the radial and circumferential strains in the ear regions were

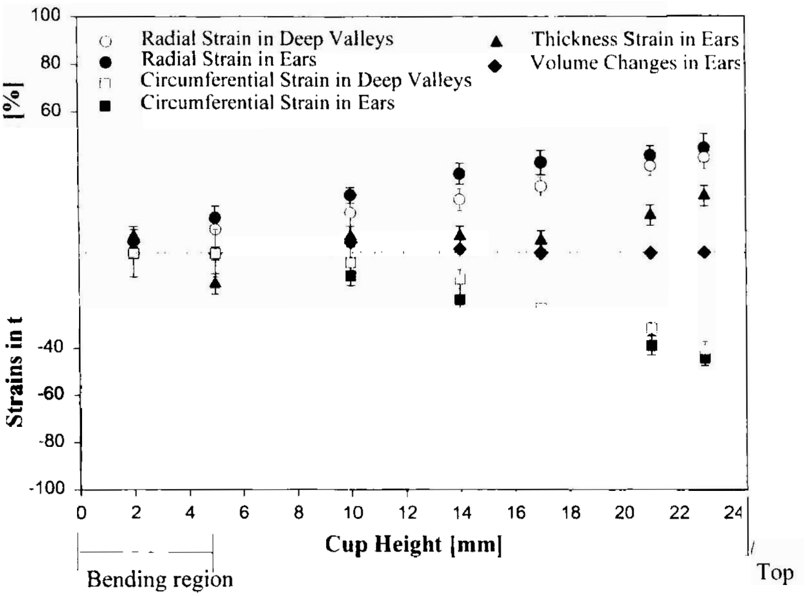

FIGURE 7 Strains in the ear and valley regions of the deep drawn cup.

5–7% higher then the strains in the valley regions. The thickness increased only at the top of the cup. The calculated volume change was negligible within the accuracy of the measurements.

Coating Failure

Relationships between the deep drawing process as described by the 4 stages in Figure 5 and coating failure were explored with two coating formulations: one that did not fail during deep drawing and one that failed. Two modes of coating failure were observed on deep drawn cups with the latter coating. In mode I failure, the coating delaminated from the metal at the top of the cup. This failure mode dominated in the buckled valley regions. In order to quantify the amount of mode I failure on the cup the debonded length was measured in the deep valley. In mode II failure, the coating lost adhesion along the cup wall. Mode II failure was not as apparent as mode I. The coating remained in contact with the metal surface after forming; however it could easily be peeled away from the cup wall. The amount of mode II failure was measured as the length of a strip peeled from the cup wall.

The punch of the deep drawing apparatus was stopped at different penetration depths and coating failure on the partially deep drawn cup was analyzed. The mode and sequence of coating failure were related to the stages of metal deformation during the process. Figure 8 shows that mode I debonding failure occurred during the buckling instability, stage III, when the cup partially lost constraint. The compressive hoop stress on the unconstrained, buckled valley between constrained ears forced the coating to delaminate from the metal at the free edge.

Mode II failure occurred at the very end of the deep drawing process, stage IV, when the entire cup lost the constraint of the blank holder and slipped into the gap between die wall and punch. The sudden loss of constraint resulted in elastic unloading of the metal. The thin coating had to follow the sudden metal retraction, which promoted microbuckling of the polymer film at flaws or places of weak adhesion. This resulted in loss of adhesion along the cup wall for the coating that was formulated to fail easily. The other coating went through the deep drawing process with neither mode I nor mode II failure.

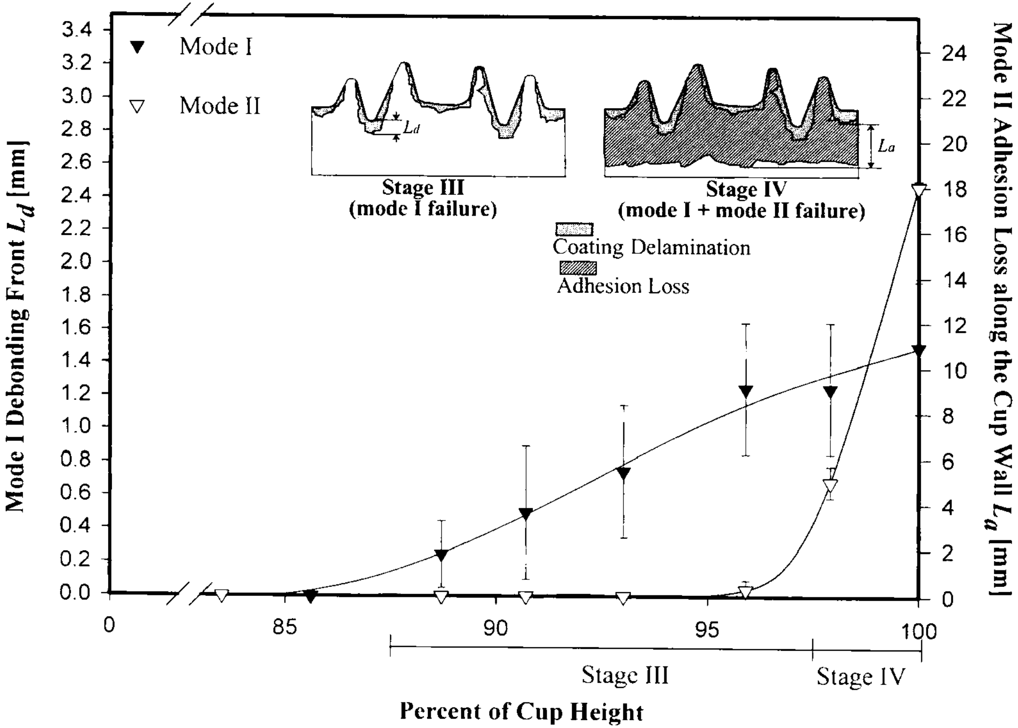

FIGURE 8 Relationship between coating failure and metal deformation in the deep drawing process; coating failure modes shown schematically in inserts.

SUMMARY

In summary, the deep drawn metal cup experiences two instabilities: earing and buckling. The resulting stresses experienced by the coating promote two types of failure. Delamination from the free edge of the cup is designated as mode I failure. Buckling of the unconstrained edge between ears is responsible for mode I coating failure. Loss of adhesion on the entire cup wall is designated as mode II failure. Mode II delamination is caused by elastic retraction of the unconstrained, drawn cup.

Strong adhesion between coating and metal substrate is an important factor in preventing mode I and mode II coating failure. However, failure may be aggravated by residual stresses in the coating that are caused by strain in the metal substrate. Strain non-uniformity, particularly in the ears and valleys at the top of the cup, results in a gradient in the residual stresses. This leads to an additional shear stress at the interface. It should be possible to modify both factors, adhesion and stress relaxation, by appropriate changes in the chemical composition of the coating.

Acknowledgements

The authors are grateful to Professor S. Nazarenko for many useful discussions that resulted from his sustained interest in this work. They also acknowledge P. Able and B. Bergman from ICI Paints for technical assistance. The generous financial support of Glidden and the ICI Strategic Research Fund is gratefully acknowledged.

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