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Investigation into the friction and wear behaviour of polymer coated steel

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Abstract. In the packaging industry, polymer coated steel is used to produce cans and other containers. One of the limitations that can limit production rates is scuffing. Scuffing is local failure of the polymer coating. To understand the failure behaviour of this type of sheet coating, cans have been produced at a range of processing speeds and tribological tests have been performed on polymer coated steel. Linear friction tests were performed under various contact pressures and tool temperatures (20-195 °C). Scuffing generated by the tests were investigated using 3D topography measurements of the surfaces. Several parameters (coating, pressure and temperature) and their interaction determines the frictional and wear behaviour of the polymer. Temperature is a key parameter governing the coating wear phenomena. Surface measurements indicate that similar coating failure defects can be observed in both the linear friction test and in industrial-scale can making. The tests proved that polymer coatings can resist relatively high contact pressure conditions and temperatures. This makes polymer coated steel sheets applicable for a large range of packaging products.

Introduction

For the production of cans and other containers, polymer coated steels have many advantages. They possess good formability and no solvents are emitted during processing. They also offer protection of the metal substrate against the filled contents [1]. However, during processing at critically high velocities, local failure of the polymer coating can occur. This local failure of the polymer coating is called scuffing.

The production of a food can consists of several steps, including drawing, redrawing and ironing. The polymer coating is subjected to a large range of temperatures and pressures during each of these steps. In the draw and redraw step, the pressures and temperatures are low in comparison to the ironing step. In the ironing step, the polymer layer is subjected to high temperatures (> 100 °C), high strain rates (> 3000 1/s) and high hydrostatic pressure (>500 MPa) [2].

The physical behaviour of the polymer coating varies within the temperature range 20-200 °C. The polymer layer has a glass transition temperature of approximately 60°C. Above this temperature, the molecules become increasingly flexible as temperature rises, until the recrystallisation temperature is reached. Recrystallisation starts at around 100 °C and this lowers flexibility again. A melting trajectory takes place at approximately 200 °C - 250 °C.

The tribological behaviour of the polymer layer during the drawing step can be investigated by linear friction testing. In this test, it is possible to assess performance at similar pressures and temperatures found in the drawing step. The strain is not taken into account in a linear friction test. Studying the tribological behaviour of the polymer layer during ironing is far more difficult due to the very high velocities, deformation and pressures. Van der Aa [3] build a strip ironing device to study the process forces and friction coefficients. The coefficient of friction decreases with decreasing die angle and increasing velocity.

The roughness development of polymer coated steels during deformation has been studied by several authors [4-6]. Faber [4] studied polymer-metal interfaces in bi-axially deformed ECCS/PET laminates and local delamination. Venema et al. [6] studied roughness development during several steps in the can making process. During the draw and redraw process, surface roughening occurs. In the first ironing stage, a large decrease in roughness is observed. In the second ironing step, scuffing was observed for one material. The behaviour of polymer coatings during ironing is relatively unknown and the recrystallisation (and other temperature related) behaviour of these coatings needs further investigation.

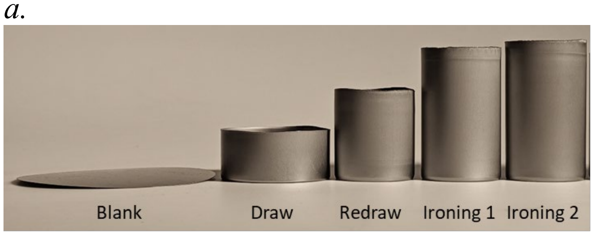
The aim of this paper is to investigate the effect of pressure and temperature on surface development and the risk of coating failure during can production. To gain further insights, cans were produced at several process speeds. Increasing process speed results in elevated processing temperatures. To assess both temperature and pressure effects on the polymer coating, linear friction tests were performed at a range of temperatures and pressures.

Can making: Material and methods

Tests using a semi-industrial can making line were performed at several production velocities, ranging from 180 to 240 cans/minute. First, around 800 cans were produced to achieve a stable machine temperature. After reaching a stable situation, production speed was increased incrementally by 30 cans/minute after every 200 cans. At higher production speeds, increased temperatures will, at a critical moment, induce scuffing in the second ironing step.

The process includes waxing, blanking, drawing, redrawing and two steps of ironing. Fig. 1a shows the progression set. The electrostatic waxer applies wax at a temperature of 65 ° to both top (49.7 mg/m2) and bottom (218.1 mg/m2). The top side of the strip becomes the inside of the can. In the cupper, blanks are punched and cups are drawn. The cups are produced using the ‘early lift off ‘principle. In the early lift off principle, the blank holder pressure is removed just before the flange material leaves the blank holder at the end of the stroke. This prevents the formation of polymer hairs as a result of the high surface pressure. In the bodymaker, a redraw step and two ironing steps occur. The tools of the bodymaker are internally cooled. The temperature of the can surface is measured between the two ironing rings by a digital infrared pyrometer, see Fig. 1b. Maximum temperatures measured are between 183 and 189 °C (at 167 and 200 cans/min respectively). Table 1 includes process settings.

a.



b.

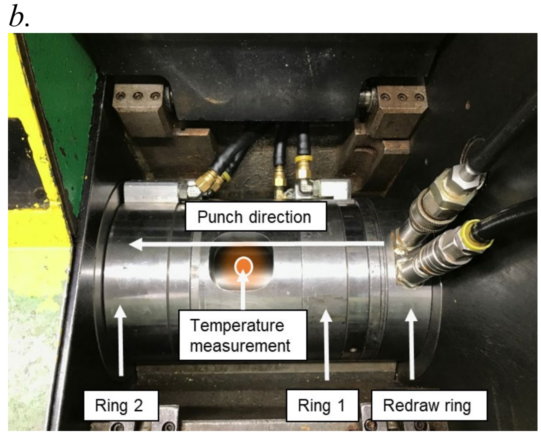


Fig. 1. a. Progression set. b. Bodymaker toolpack.

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Table 1. Process settings.

Cupper		**Bodymaker**	
Blank Holder force [bar]	1.17	Redraw diameter [mm]	66.41
Cupping speed [n/min]	140	Ironing ring 1 diameter [mm]	65.896
Punch size [mm]	88.71	Ironing ring 2 diameter [mm]	65.891
Blank size [mm]	149.94		
Draw ratio [-]	1.69		

Cans were produced from laminated Electrolytic Chromium Coated Steel (ECCS) with Poly-Ethylene Terephthalate (PET) on both sides (20 µm outside/30 µm inside) with a thickness of 0.25 mm. The wall thickness reduces after the first ironing ring to 0.168 mm (44% reduction) and after the second ironing ring to 0.158 mm (6 % reduction).

Three dimensional topographical measurements were performed using the NanoFocus µsurf mobile confocal microscope. To enable measurement of the polymer coating, a thin layer of gold was sputtered onto the surface of the cans.

Can making: Results

At a production speed of 240 cans/min, scuffing started to appear on the top side of the can. Fig. 2 shows the confocal measurements at position 100 mm from the base of the can. The appearance of the coating failure is not always exactly the same, and depends on the exact local conditions such as temperature, pressure and strain. In this investigation, a higher processing speed results in a higher surface roughness which is probably related to the increase in temperature. The surface roughness Sa (average of 3 measurement values) is 0.71 and 0.89 µm for 180 cans/min and 210 cans/min, respectively.

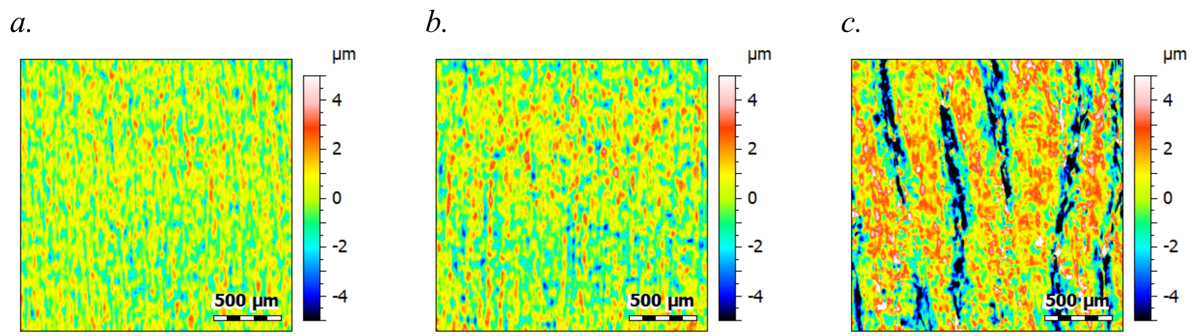

Fig. 2. Confocal measurement of surface of can at a. 180 cans/minute b. 210 cans/minute c. 240 cans/minute. Drawing direction from top to bottom.

Tribological investigation: Materials and methods

An experimental method was employed to evaluate the tribological behaviour of the polymer sheet coated material for a range of pressures and temperatures. The experiments were performed using a Linear Friction Tester (LFT) capable of providing controlled contact conditions between the tool surfaces and the polymer coated sheet, see Fig. 3a. Tool A (Sa = 0.12 ± 0.02) is cylindrical with a diameter 20 mm. Tool B (Sa = 0.12 ± 0.02) has a large radius of 300 mm. The tools were heated by an internal heating element to a specific temperature between 20 by 195 °C. The tools close upon the moving strip. The force builds up during the displacement of the strip. Tests with a normal force of 2, 4 and 8 kN were performed. The average coefficient of friction value was determined between 80-100 mm of the total drawing length of 105 mm.

A laminate of Electrolytic Chromium Coated Steel (ECCS) with Poly-Ethylene Terephthalate (PET) on both sides (20 µm inside/30 µm outside) with a thickness of 0.25 mm was used in the LFT investigation. Two sheets (50x300 mm) were pasted together with tape on the top and bottom before the test to ensure stability and avoid deformation. The 20 µm PET coating is in contact with the tools.

Three dimensional topographical measurements were performed using the NanoFocus µsurf mobile confocal microscope. To enable measurement of the polymer layer, a thin layer of gold was sputtered on the surface. The confocal measurements are performed at 50 mm sliding distance (middle) on both sides.

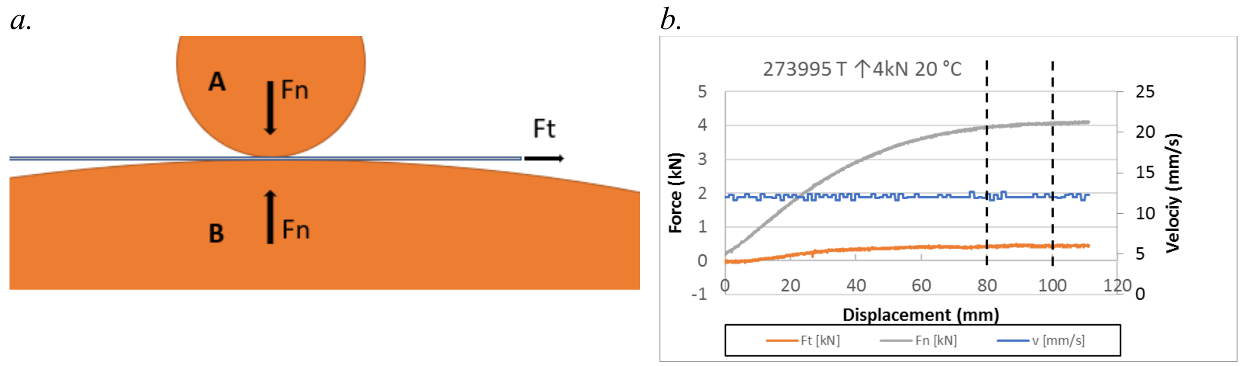

Fig. 3. a. Schematic view test b. Normal force, tensile force and velocity versus displacement.

Tribological investigation: Results

To investigate scuffing behaviour, a matrix of LFT tests were performed at different pressures and temperatures. Scuffing is observed on both sides of the PET coated samples, however more severe scuffing is observed on the side in contact with Tool B (large radius). The contact area is higher for Tool B than for Tool A and more heat can, therefore, be transferred from the tool to the sheet. The pressure is lower on tool B which will have an opposite effect on the heat transfer. Besides heat transfer, contact pressure has also an effect on scuffing. Thus several aspects play a role, which are not easy to untangle due to the set-up of the test (different tool geometry on both sides). Finite element simulation could provide further insight into local temperature effects.

Fig. 4 shows surface appearance after testing at different temperatures. The confocal measurements shows a very smooth coating surface after testing at 150 °C. The surface roughness Sa is between 0.2 - 0.25 µm (depending on normal force) for temperatures of 20-100 °C. A large drop in surface roughness to a value of 0.1 µm occurs at 150 °C. This drop could be related to recrystallisation, but this needs further investigation.

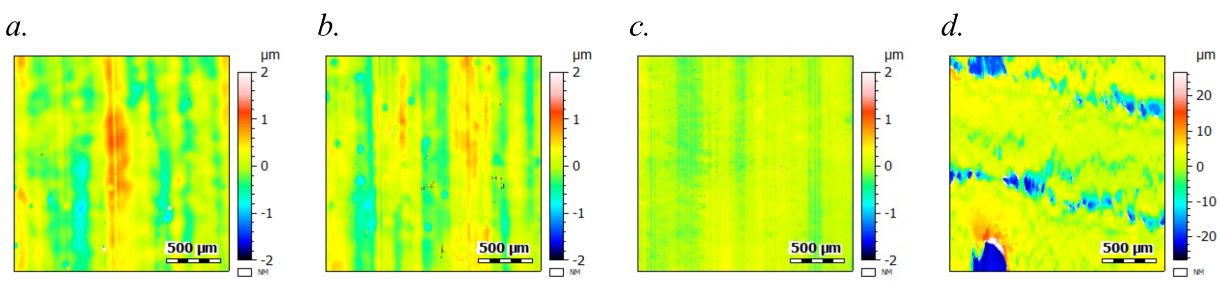

Fig. 4. Confocal measurements (2x2mm) sheet surface with tool temperature of a. 20 °C b. 200 °C c. 150 °C and d. 195 °C. Fn=4kN test – side with large radius tool

Scuffing occurs at 195°C at loads of 4 and 8 kN. The scuffing is not homogeneous over the surface, thus the severity of the scuffing depends on the exact measurement position. The depth of the scuffing is approximately the coating thickness. At 2 kN, no scuffing is observed at any of the temperatures tested, only whitening (degradation) of the coating. The most severe scuffing is observed in the 4 kN test (Fig. 5).

Fig. 5. Photograph of samples for tool temperature of 195 °C with normal force of a. 2kN, b. 4 kN and c. 8 kN. Tool side with large radius. Drawing distance from right to left.

Tribological investigation: Coefficient of Friction (COF)

Fig. 6 shows the average COF between 80-100 mm drawing distance for all tests conducted. In general, between 20-150°C, the COF decreases as temperature increases. Beyond 150 °C, the COF increases again. At 2 kN force, a negative value is measured for 150 °C. This is unexpected and should be further investigated. Scuffing occurs at 195 °C for 4 and 8 kN normal load, and results in a sharp increase in COF. Degradation of the coating, but no severe scuffing, is observed for 2kN, this resulted a lower COF value than the two other higher normal forces at 195 °C. In general, a lower force results in a lower COF.

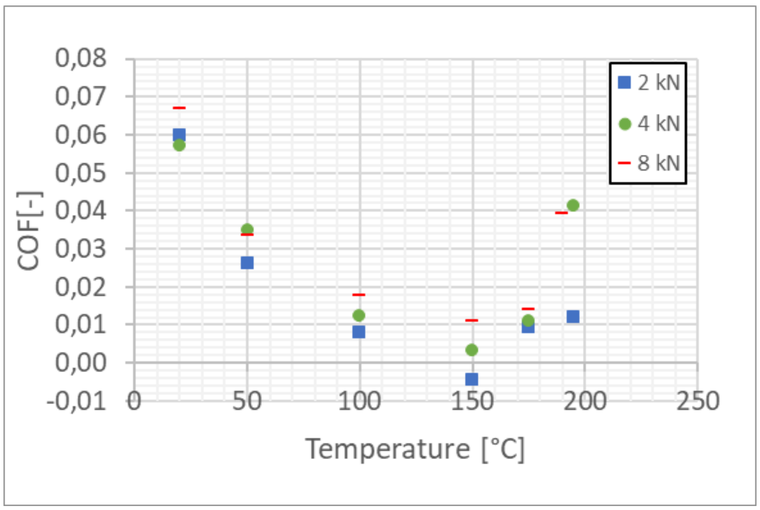

Fig. 6. COF versus temperature.

Discussion

Scuffing occurs in the can making line during the second ironing step. The temperature of the can is ~ 185 °C between the first and second ironing step. Scuffing occurs in the LFT tests at a temperature of 195 °C for normal forces of 4 and 8 kN. The appearance of the scuffing defects generated is dependent on local conditions and is different for both tool sides in the LFT tests and for cans from different tests series (Fig. 7). However, similar appearances were observed in the can making line and the LFT test under some circumstances. Cross sectional analysis will be performed to investigate the failure mechanism found in both tests. The results of the LFT are encouraging and show that the test could provide a promising method for the investigation of scuffing.

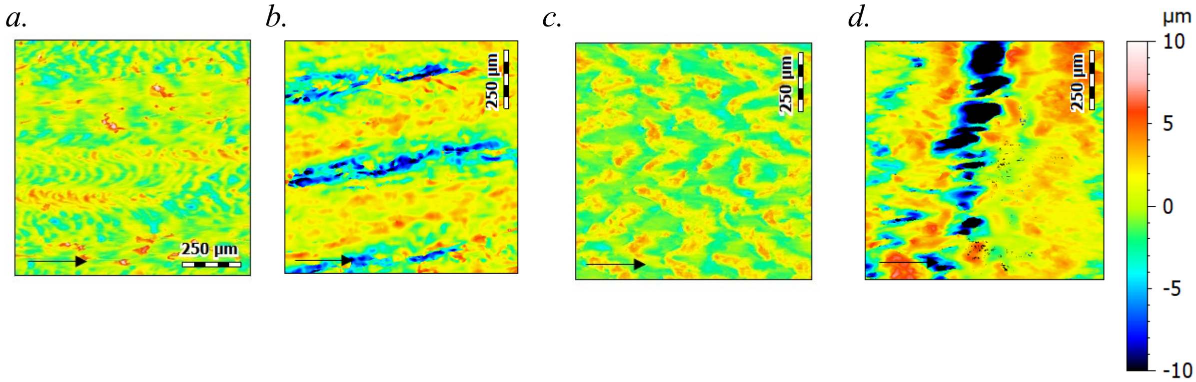

Fig. 7. Confocal measurement 1 x 1 mm of a. Can from earlier investigation [6], b. Can 240 cans/min, c. LFT side Tool A, d. LFT side Tool B.

Conclusions and recommendation

A study was performed to investigate the tribological behaviour and surface appearance of PET coated steel at different can processing speeds, for a range of tool temperatures and pressures. The tribological behaviour of the PET coating is defined by a complex combination of mechanisms. Several parameters (coating, pressure, temperature) and their interaction determines the frictional behaviour of this product. Temperature is a key parameter governing the coating wear phenomena. In the LFT test, scuffing only occurs above a certain temperature level (195 °C). In can making tests, scuffing only occurred above a certain processing velocity. Pressure has also a clear effect on scuffing. Surface measurements indicate that similar coating failure defects can be observed in both the linear friction test and in industrial-scale can making. This needs to be investigated further by cross sectional analysis. The tests proved that the polymer coating can resist high contact pressure conditions and temperatures. This makes polymer coated steel sheets applicable for a large range of packaging products.

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