Evaluating chill-roll materials and coatings with regard to heat transfer performance

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ABSTRACT: The author addresses the heat transfer analysis that is useful for users of chill rolls, in particular for those needing to know how the outer shell design and material will affect the immediate and long-term performance of the roll. The last section of the paper discusses chromium plating and finishes.

KEYWORDS: Chill rolls, chromium, design, finishes, heat transfer, materials, performance evaluation, plating, shells.

The trend in extrusion coating is to increase rubber-roll nip pressures against the web and chill roll. In our experience, some coaters are approaching 300-pli loads. This load is comparable to extruded film products.

The advantage of high loads is improved adhesion to the board and better heat transfer to the cooling roll. The increased heat transfer is due to a wider zone of contact from the rubber roll deflection and probably a decrease in the air film between the web and the chill roll.

High nip loads make correct roll design more important. The roll construction must be rigid to ensure uniformity of heat transfer and gauge.

Many roll designs are based on an intent to improve heat transfer without considering the deflection of the outer shell. It is easy to design a roll that is very expensive to fabricate and maintain but that has little or no performance advantage.

Deflection

In the following discussion, we will consider roll shells that are not shrink fitted to the inner spiral and shell assembly.

If one is considering aluminum as an alternative to steel, it is not possible to shrink fit or weld the outer shell, or it eliminates the advantages of removable shell designs.

In our case, the outer shell can be considered a simple supported tube with a uniform load. Maximum deflection (Y_{max}), as shown by Roarks (*1*), is

$$Y_{max} = -5W(L^4)/384 \times EI$$

where

W = force, pli

L = face length, in.

E = Young's modulus

I = moment of inertia.

$$I = \pi R^3 t$$

where

R = mean radius, in.

t = wall thickness, in.

Obviously, to have roll designs of dissimilar materials deflect equally, the product EI must be constant. Consider three materials:

1. Carbon steel
2. Aluminum alloy
3. 316 L stainless steel.

From Section 5-5, Table 3 of *Marks' Standard Handbook for Mechanical Engineers* (*2*)

$E_{Al} = 10(10^4)$

$E_{st} = 30(10^6)$

$E_{316L} = 29(10^6)$.

From a deflection standpoint, steel and stainless steel can be considered to have the same rigidity. Aluminum is one third as rigid, meaning that a simply supported aluminum tube must have a thicker wall. In a 24-in. x 1/2-in.-thick steel shell,

$$I = \pi(11.75^3)(0.5) = 2.55 \times 10^3 \text{ in.}^4$$

I_{Al} must be three times greater. In this case, this amounts to an approximately three times thicker outer shell. For a 24-in. x 1.75-in. wall or 25.75-in. x 1.375-in. wall,

$$I_{Al} = \pi(11.125^3)(1.75) = 7.56 \times 10^3 \text{ in.}^4$$

$$I_{Al} = \pi(12.19^3)(1.375) = 7.8 \times 10^3 \text{ in.}^4$$

Overall heat transfer coefficient

Looking at the heat transfer of relative materials, we must have a reasonable model of the heat exchanger (chill roll). In this case, consider one spiral section of the 24-in. x 1/2-in. steel chill-

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roll of unit length, a 24-in. x 1.75-in. aluminum alloy roll, and a 24-in. x 1/2-in. 316L roll. Polyethylene (PE) equal to 0.001 in. is being extruded on the roll surface. A 5/8-in. deep x 3-in.-wide channel is typical, with water at 60°F and flowing at 10 ft/s (**Fig. 1**).

The heat flow (Q) of any heat exchanger is defined by:

$$Q = UA\Delta T$$

where

U = overall heat transfer coefficient

A = effective area

ΔT = temperature difference between film and water.

The intent of this paper is to focus on the controlling factors of heat transfer in the chill roll. Free convection from film to air and conduction from film to board is negligible. This will be obvious when we complete our analysis of the model and observe the relative order of magnitudes of the primary coefficients.

We will simplify our math by using a unit area of the model and considering the area flat.

For any given roll, size, and process U becomes the controlling variable. In other words, how well can heat leave the PE, conduct through the metal shell, and transfer to the water?

From Marks (*2*) Section 4, Eq. 4,

$$U = 1/(1/h_{H_2O}) + (t/k_{\text{roll matl}}) + (t/k_{PE})$$

From Marks (*2*) Section 4, Eq. 6c, h_{H_2O} can be calculated to be approximately 1800 Btu/h/ft²/°F. This is reasonable when comparing h_{H_2O} values in Marks (*2*) Section 4, Table 9.

From Marks (*2*) and *The Modern Plastics Encyclopedia* (*3*) our K values are:

K_{steel} = 26 Btu/h/ft²/°F

K_{316L} = 7.5 Btu/h/ft²/°F

K_{al} = 64 Btu/h/ft²/°F

$K_{poly\,E}$ = 0.19 Btu/h/ft²/°F

$U_{steel} = 1/(1/1800) + [(0.5/12)/26] + [(0.001/12)/0.18] = 1/(5.6)(10^{-4}) + (1.6)(10^{3}) + (4.6)(10^{-4}) = 382$ Btu/h/ft²/°F

$U_{316L} = 1/(1/1800) + [(0.5/12)/7.5] + [(0.001/12)/0.18]$

$U_{316} = 1/(5.6)(10^{-4}) + (5.5)(10^{-3}) + (4.6)(10^{4}) = 153$ Btu/h/ft²/°F

$U_{Al} = 1/(1/1800) + [(1.75/12)/64] + [(0.001/120/0.18]$

$U_{Al} = 1/(5.6)10^{-4}) + (2.28)(10^{-3}) + (4.6)(10^{4})$

$U_{Al} = 303$ Btu/h/ft²/°F.

Several important points should be noted:

1. In the extrusion coater situation, the shell material can control the overall heat transfer efficiency. This is unusual in most heat exchanges.
2. In the extrusion of thick film and sheets, the increased thickness of the polymers can cause the thermal resistance of the polymer to dominate the equation, and the shell material will not be of great importance in the overall heat transfer equation.
3. The necessary increases in wall thickness for aluminum shells can quickly affect the thermal conductivity advantage.
4. Selecting a high-conductivity roll shell without consideration of the overall heat transfer factors can have an adverse effect on roll performance.

Scaling and anti-fouling

Up to this point, we have neglected a very important aspect of overall heat transfer performances: thermal resistance due to scaling of the water passages.

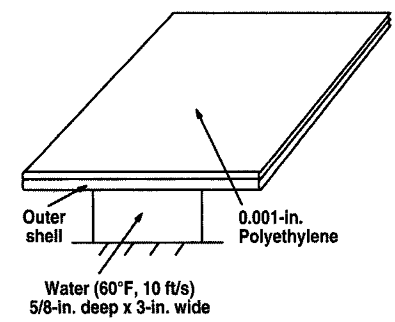
Marks (*2*) Section 4, Table 8, gives some h values for scale deposits from water: treated makeup $h = 1000$, hard water $h = 330$.

A more valid formula for overall heat transfer coefficient is

$$U = 1/(1/h_{H_2O} + (t/k_{shell}) + (t/k_{PE}) + (1/h_{scale})$$

The scale component can become

1. The heat exchanger



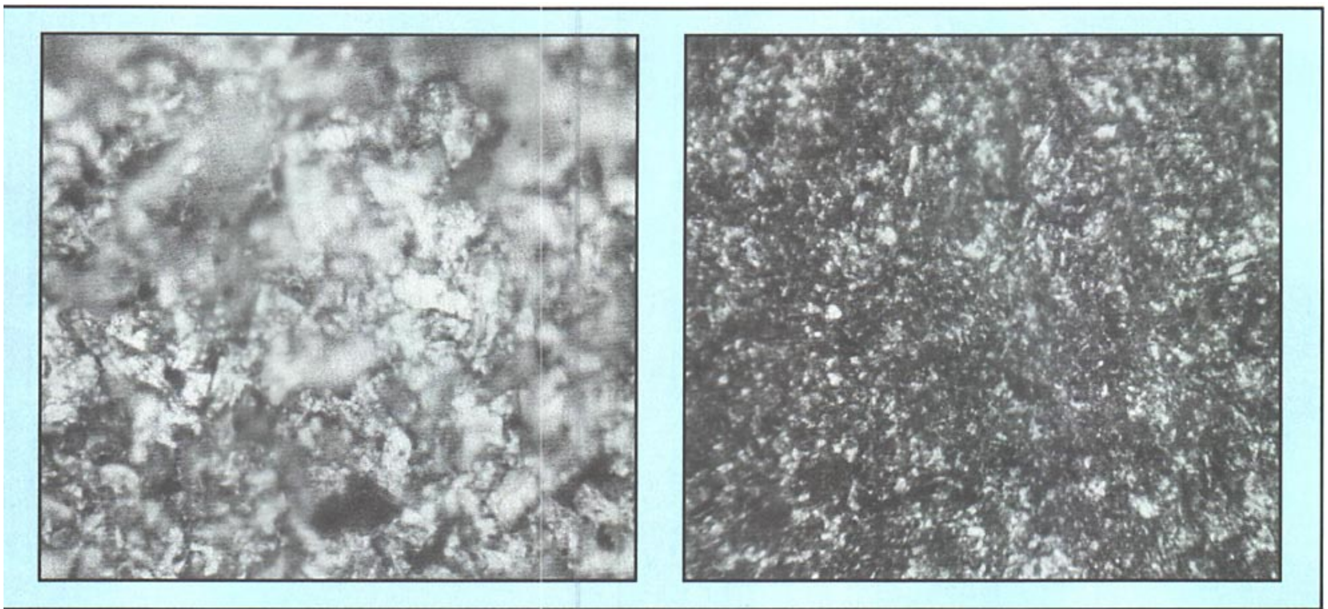
equal to or greater than the thermal resistance of the shell. In the best case of treated water, the scale component is close to the thermal resistance of the cooling water.

In fact, most operations have had problems due to scaling, and a number of techniques have been developed to solve the problem, including coating of water channels and removable shell-roll designs.

Removable shell rolls are primarily designed to allow disassembly and cleaning of the roll interior. Unfortunately, this design does not allow the inner spiral to help stiffen the roll shell. The increase in nip loads and the possibility of overloading a drive or wrapping a nip will cause an out-of-round condition in these rolls that must be adjusted. Furthermore, the advent of better water treatment and biodegradable descaling chemicals makes the removable shell less of an advantage.

Removable shell rolls are more expensive to build than conventional welded rolls. The outer shell must also be heavier than shrink-fit rolls of comparable stiffness. Our experience in rebuilding and repairing these rolls is that few operations have the time or expertise to disassemble the rolls for cleaning and to adjust them for correct runout.

2. 100 rms soft matte, etched after plating (left = 100X, right = 400X)



There is a new, proprietary design with a fixed shell which allows cleaning of individual cooling channels.

Over the years, much discussion has been placed on anti-scaling materials or coatings for the shell interior and water passages. No technical data supports the fact that coated internals will scale less quickly than slightly oxidized steel shells.

In the case of welded construction rolls, coating of the interior can be practically accomplished prior to assembly of the outer shell only. There is no way to guarantee that a used roll can be thoroughly cleaned to the level that is necessary to achieve a clean bond area. An improperly bonded, anti-scaling coating will have adverse effects on heat transfer due to water trapped in blisters or other defects; the coating itself becomes a scale.

Electroless nickel and chrome plating have been used on water passages. It can be argued that these coatings will slow or prevent oxidation of the metal passages. However, there is no evidence of the coating preventing mineral deposits or other scale.

If operators or designers of chill rolls are set on anti-scaling materials, it is appropriate to use Teflon® or other similar materials. Using our previous heat transfer model, we can demonstrate that they will not have an adverse effect on performance if they prevent scaling.

From the *Electroplating Engineering Handbook* (*4*):

K_{EN} = 0.009 Btu/ft²/s/°F/in.

= (60)(60)(0.009)

= 32 Btu/ft²/h/°F/in.

From DuPont

K_{Teflon} = 1.7 Btu/ft°/h/°F/in.

Thermal resistance (0.002-in. thick) EN

= 0.002/32

= 6.2×10^{-5} Btu/h/ft²/°F

Thermal resistance (0.001-in. thick)

Teflon = 0.001/1.7

= 5.9×10^{-4} Btu/h/ft²/°F

Thermal resistance scale

= 1/300 to 1/1000

= 3.3×10^{-3} to 1×10^{-3} Btu/h/ft²/°F

Chromium plating

Chromium electroplate has become a standard roll coating in the plastics and paper industries. In the previous analysis we have seen that even thin films can have an effect on overall heat transfer coefficient (*4*):

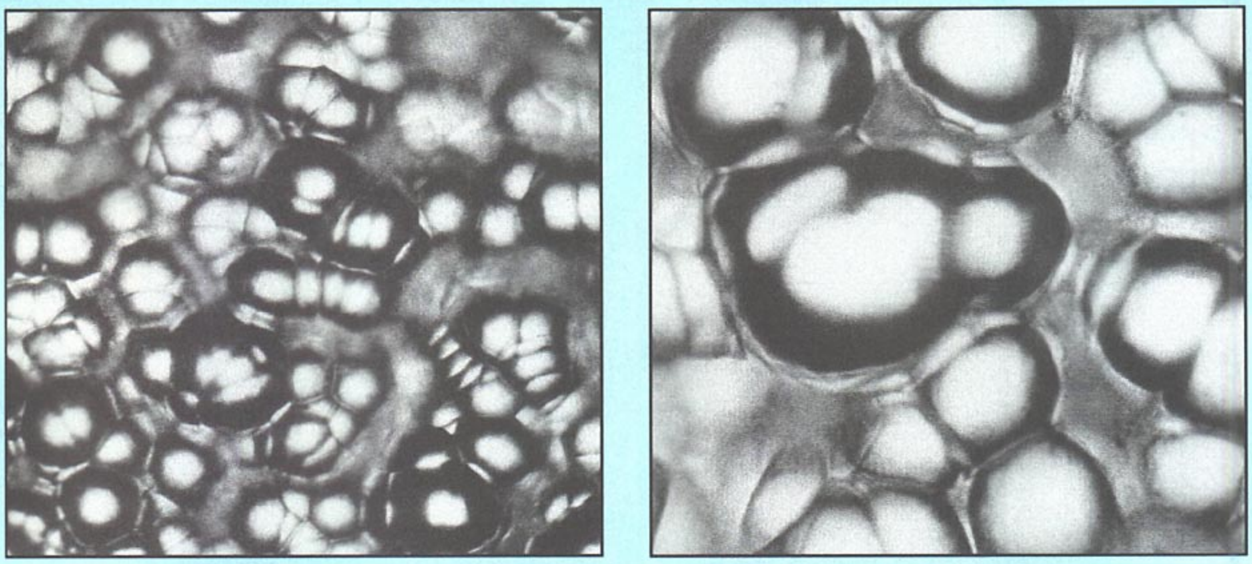
$K_{Chromium}$ = 54 Btu/ft²/h/°F

Chromium roll deposits are typically in the range of 0.005 in. after grinding.

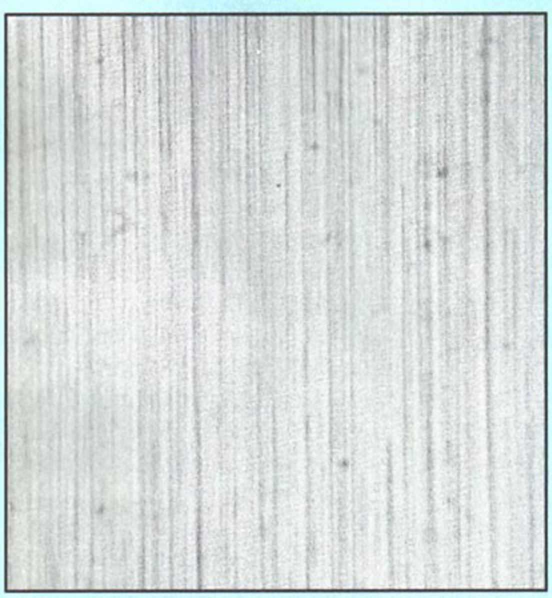
The thermal resistance of the film of chromium is 0.005/12/54, 27.7×10^{-6} Btu/h/ft²/°F.

The technology of chrome deposition has not substantially changed in 50 years. Despite this, there are quite a few misconceptions about chrome plating. Chrome, like all electroplates, is a mechanical bond, not a metallurgical bond. This means bond strength will decrease with increased deposit thickness. Chrome is very hard but has low tensile strength. It is easily cracked by rapid changes in temperature or improper grinding. Rolls can be plated vertically or rotated horizontally. Most platers of large rolls use both techniques. There is no metallurgical difference in the deposit. Chrome plate as deposited is 99.9% technically pure metal. Hydrogen is generated at the plating surface. Hydrogen becomes trapped in the crack pattern of chrome and will diffuse with temperature rapidly. In cases when hydrogen may mark film, rolls can be heated to 180–375°F to

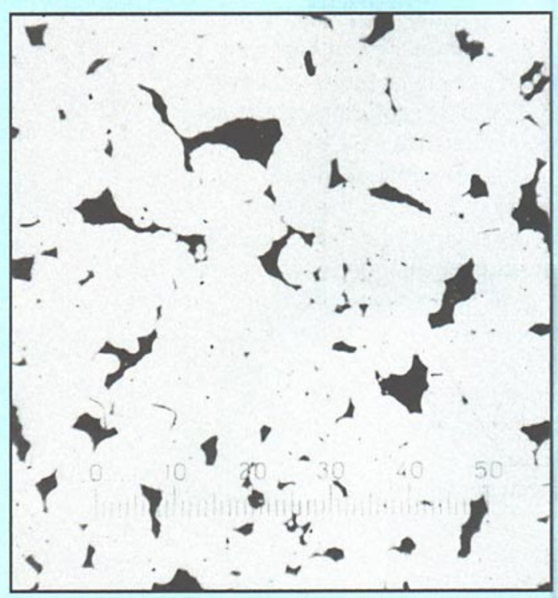
3. 200 rms hard matte surface, etched before plating (left = 200X, right = 400X)



4. 2–4 rms surface, ground and polished after plating (100X)



5. 18–20 rms pocket finish (50X)



rapidly relieve the gas. Bake-out will not affect the hardness of the deposit.

In comparison to other hard coatings, especially thermal sprays, the deposit is very dense. (Thermal sprays are typically 2–8% porous by volume.)

Chromium finishes

Chromium has become a widely used roll coating because it can be finished to a large range of roughnesses (from less than 0.5 RMS to 400 RMS) and textures.

Producers of film and laminates require numerous textures and gloss. Because chromium plate can be worked by grinding, polishing, superfinishing, and chemical and mechanical etching, an infinite range of textures is available.

Figures 2–5 show four types of finishes used by film and coextruders: soft matte, hard matte, polished, and pocket. Each type of finish affects gloss, roughness, emboss, and release differently.

Roll finishing shops that specialize in chrome-plating rolls must be well equipped with precision roll-grinding and other machine tools. The quality of these roll finishes is determined by the quality of tooling, the ability to measure replication, and experience in the film industry.

Conclusion

We hope that this paper has provided some insight into heat transfer and coating of chill rolls.

Technical people who do not work in this field on a regular basis often have not had the time to become involved at the roll design stage.

We hope this paper will at least promote the questioning of some popular misconceptions about chill rolls. ■

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