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ROLL DESIGN
A REVIEW OF THE BASICS

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Abstract

Over the years many advances have been made in the production of flat sheet in the areas of die design, screw design, and polymers. However the design of a critical part, the cooling roll, is often given little consideration by the processor. The intent of this paper is to review some of the parameters that the roll designer uses to determine the design of the roll. The basic equations for calculating PLI (pounds per linear inch), and deflection of the roll, the heat removal rate required, and a method for approximating the required flow rate through the roll are explained.

Introduction

The purpose of this work is to review the basic design of the cooling roll as it applies to the sheet producer. The main items that will be discussed are the calculations that are used to determine the construction of a typical cooling roll. This will consist of four basic calculations: roll loading (PLI), roll face deflection, heat removal rate, and coolant flow rate (GPM). We will discuss these calculations and how they can assist the processor in solving some common situations that occur in the cooling roll stand of a sheet line.

It has been observed that many of the rolls installed in older existing sheet lines, have been built using little or no technology. Although the rolls have been reconditioned many times over their life, no consideration has been given to, updating the design or how the current design affects the sheet being produced. Here we will look at some of these factors, and provide a method of evaluating the current design and a means to collect information that will lead to more effective roll designs.

Roll Loading (PLI)

The roll closing force that is applied to the sheet by the actuation system is considered the roll loading or often referred to as PLI (pounds per linear inch). For the purpose of this discussion an air or hydraulic cylinder actuation system will be used as an example. The components of the actuation system that are considered in determining the roll closing force are, the cylinder size and the pressure provided by the air/hydraulic system.

To determine the roll closing force, the area of the cylinders must first be determined using the following equation.

$$A = (\Pi D^2)/4 \tag{1}$$

A= cylinder area (inch²)
D = cylinder diameter (inch)

The area is then substituted into equation (2) along with the system pressure and the length of the loaded roll face. The result is the roll closing force as shown by equation (2).

$$PLI = (2 \times A \times P)/L \tag{2}$$

PLI = roll loading (pounds per linear inch)
A = cylinder area (square inches)
P = system pressure (p.s.i.)
L = length of load on roll face (inches)

(If the cylinders are connected to the roll by means of a lever arm, the force multiplier must be used to increase the PLI)

It is important to note at this point that the system pressure used is typically the maximum pressure that is available to the system. However the actual pressure that is transferred by the polymer to the roll is usually somewhat less than the system pressure due to the fluidity of the polymer. The actual pressure is dependent on the roll gap, roll diameter, polymer temperature, polymer characteristics, and solidification point of the polymer. In a typical roll stack the cylinder pushes the movable roll arm against an adjustable stop. Therefore a stand rated at 400 PLI, is capable of applying that load on the stops, however it does not necessarily mean that the material being processed is transferring that load to the rolls.

The common practice to determine the actual load being transferred is to decrease the system pressure until the roll begins to “float” or move off of the adjustable stops. This is usually accomplished by using a dial indicator placed against the movable roll arm. By

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*When the paper was presented, the author was affiliated with New Castle Industries Inc., which was acquired by Xaloy in 2003.

substituting the transfer pressure back into equation (2), the actual transferred PLI can be determined. This experimental method for determining the transfer pressure applies only to the polymer and the conditions used in the test. On a line that runs a wide variety of materials, it can be seen that the transfer pressure will vary between resins, gages and process conditions. This helps to explain why the variation in the cross line direction of the sheet changes with only a change in the thickness of the sheet being produced. For example thin sheet which cools and solidifies quickly will transfer more load to the roll than thick sheet which cools slower.

This information combined with the deflection calculations in the next section will allow the process engineer to calculate the true bending of the roll relative to the transferred load. This can then be compared to the gage variation found in the sheet to determine what portion of the variation can be attributed to the roll, and what can be attributed to other items such as bearing run out, stand flexure and die flow.

Deflection

In many cases, when dealing with the rolls found in older sheet lines, the type of rolls found are: single shell or cooling can type rolls. (See Figure 1 and 2) When a load is applied to one of these rolls, only the outer shell supports the load. This results in substantial bending of the roll, which contributes to gage variations in the final product. Increasing the thickness of the shell would offset the bending, however this option is impractical due to an effort to maintain good heat transfer. Therefore the deflection of the roll body can not be independently controlled. The deflection of this type of roll can be calculated by equation (3).

$$Deflection = \frac{5 \times PLI \times L^4}{384 \times E \times I} \tag{3}$$

L = length of load on roll face (inch)
E = modulus of elasticity (p.s.i.)
(29,000,000 for steel)
I = moment of inertia (inch ^{4})

$$I = \pi (D^4 - d^4)/64$$

D = shell outside diameter (inch)
d = shell inside diameter (inch)

The use of double shell, spiral baffled roll construction has been developed to address both the heat transfer concerns as well as the bending. (See Figure 3) Using this construction method one can design a roll that controls the current outer shell thickness, while maximizing the heat transfer abilities, by utilizing both the inner and outer shell to support the given load. By combining the moment of inertia of both shells the result is a much stronger roll with less deflection and improved heat transfer characteristics. The bending, for a double shell roll with rigid support between the shells can be described by the following commonly used formula.

$$Deflection = \frac{5 \times PLI \times L^4}{384 \times E \times (Io + Ii)} \tag{4}$$

Io = outer shell moment of inertia (inch ^{4})
Ii = inner shell moment of inertia (inch ^{4})

It should be noted that the variable that has the most affect on the deflection of the roll is the face length (L), as it is used to the fourth power of the loaded roll face. (See Figure 4) Hence longer rolls bend much more. Therefore using the design of a roll built for a narrow line, that is performing well, and "stretching" it for use in a wide line is impractical due to a large increase in the deflection. The negative result to the processor would be in the form of "out of tolerance sheet" as well as the poor economics of producing lens shaped sheet. (i.e. using more resin to maintain minimum thickness)

Heat Removal Rate

A comment that is frequently heard from processors is "I have changed the material that I am processing or line speed and now I am unable to cool the sheet properly". This is a common problem that usually leads to investigating the cooling roll. The first step is to determine the heat removal rate that is required for the materials being processed. By calculating the heat removal rate for the various materials being processed you can determine the worst case heat load and have the rolls designed for that condition.

To calculate the heat removal rate, first some data must be obtained from the line. The data required is as follows: the output rate of the extruder, the melt temperature at the die, the desired exit temperature from each cooling roll, and the specific heat of the polymers being processed. Armed with this information the heat removal rate can be determined using the following formula.

$$Q = O \times \Delta T \times Cp \tag{5}$$

Q = heat removal rate (BTU/hr)
O = extruder output (lb/hr)
Δ T = temperature change, on to off (°F)
Cp = specific heat of polymer (BTU/lb°F)

A table of heat removal rates by polymer and specific running conditions for that polymer can be an invaluable tool, not only for the roll designer but for the processor as well. It can show which products have the highest heat loads, which is vital for a successful roll design. It will allow the roll designer to determine if the roll is undersized for specific products. By using the worst case heat load and the equations found in the next section, the coolant flow rate for each product can be calculated enabling the processor to determine if the cooling system has an adequate supply of coolant.

Coolant Flow Rate

Flow rate relates to cooling rolls in two ways. The first is the coolant flow rate as it relates to the temperature variation across the roll face. The second is having sufficient flow to remove the required amount of heat. Although both of these are important to the overall effectiveness of the roll, by investigating the temperature variation across the roll face, conclusions can be drawn indicating if the flow rate is sufficient for the heat load. This is a relatively simple method to approximate the flow rate required for a given heat load. You will note that the equation that follows does not take into account: line speed, sheet thickness, or wrap angle, which would require a more in-depth analysis. Its focus is on the bulk heat load, which is an excellent starting point, and the results can be easily compared to actual data obtained from the sheet line.

The comparison data can be obtained simply by installing a flow meter in the inlet line of the cooling roll, which allows continuous monitoring of the flow that is available to the roll. Additionally temperature indicators should be installed at the inlet and outlet of the roll providing the temperature differential across the roll.

By definition the British Thermal Unit (BTU) is the amount of heat required to raise the temperature of 1 lb. of water 1°F. We can use equation (6) to calculate the flow rate required for a 1°F rise in the coolant temperature. The heat removal rate (Q) calculated from equation (5) is substituted into equation (6). The result is the flow rate required for a 1°F rise in the fluid temperature at the calculated heat load. Based on equation (6) it can be observed in Figure 5 that the coolant flow rate has an inverse straight-line relationship to the temperature differential.

$$GPM = Q / C \qquad (6)$$

GPM = flow rate for 1° rise (Gal/min)
Q = heat removal rate (Btu/hr)
C = conversion factor (500.4)

Once the flow rate is determined using equation (6) the theoretical temperature variation across the face can be determined using equation (7).

$$Tv = GPM / GPM' \qquad (7)$$

Tv = temperature variation
GPM = calculated coolant flow rate (Gal/min)
GPM' = observed coolant flow rate (Gal/min)

Most sheet products can be processed satisfactorily with more than 1ºF temperature rise. Determination of the maximum acceptable temperature rise can be done experimentally or by heat transfer analysis.

A large difference in the observed verses calculated temperature variation (Tv) could indicate a loss in the heat transfer capability of the roll. This is often due to corrosion or scale build up in the internal flow passage of the roll. Any such coating of the ID of the outer shell will reduce heat transfer, and in some cases block the flow channel. This could be corrected by removing the outer shell cleaning the internals and installing a new shell.

By rearranging equation (7), selecting a desired value for Tv, and solving for GPM', the result can be compared to the flow rate observed on the flow meter. If the flow rate on the flow meter is substantially less than GPM' it could indicate insufficient flow is being provided by the cooling system. Either case indicates an upgrade to the existing components is required.

Conclusions

The information provided here, and the results that can be obtained from the equations provide a better working knowledge, of four, of the many factors that are involved in the design of the cooling roll. These ideas will assist in analyzing on line situations. In addition this will aid in specifying new or replacement rolls that will overcome some of the common process issues.

References

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Keywords

PLI, Deflection, Rolls

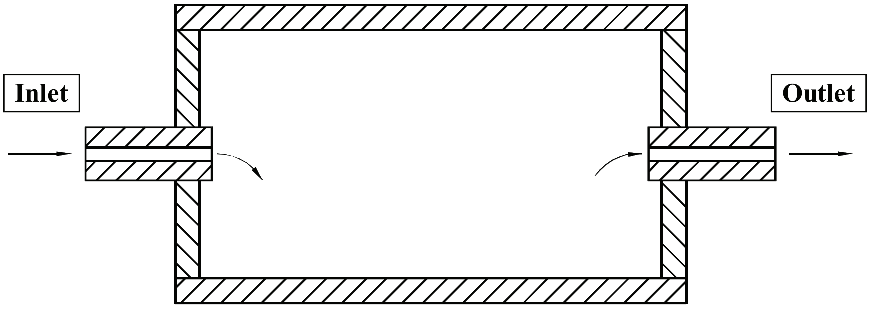

Figure 1
Single Shell Roll

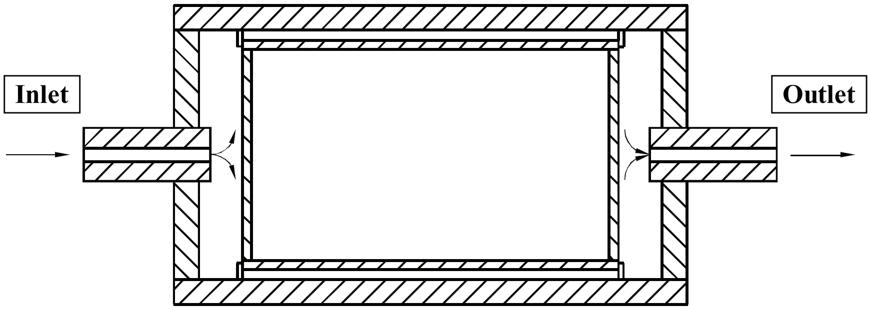

Figure 2
Cooling Can Roll

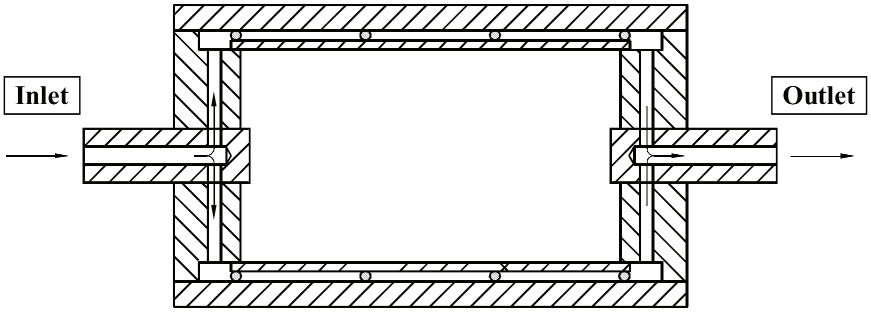

Figure 3
Double Shell Spiral Wrapped Roll

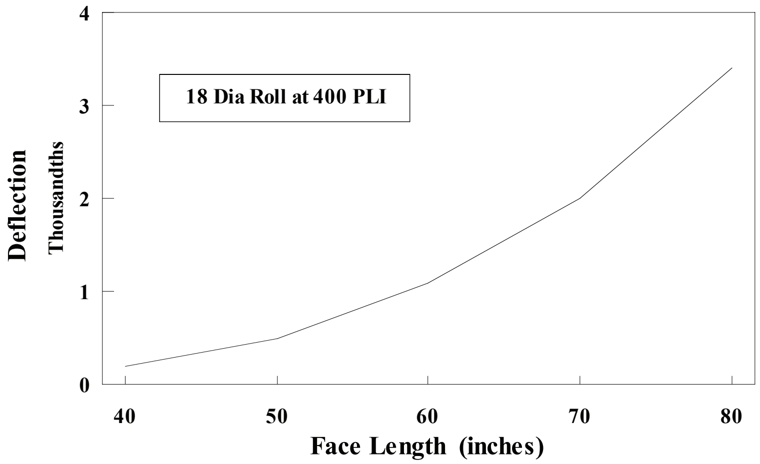

Figure 4

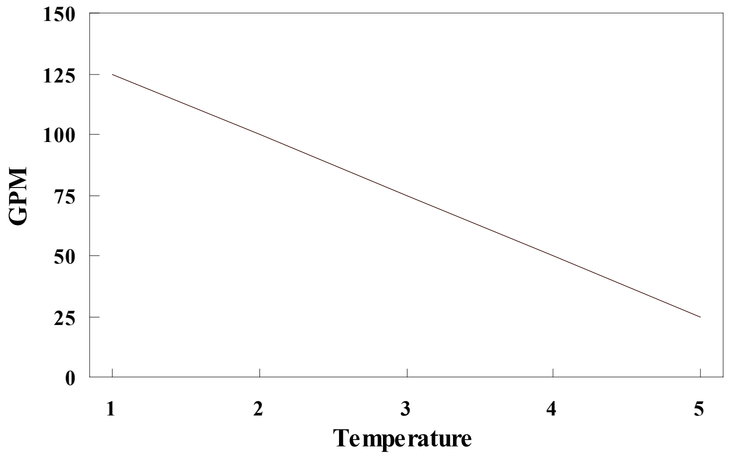

Figure 5

Table 1

Polymer Type	Specific Heat	Specific Gravity
PC	.30	1.20
PS	.32	1.09
PP	.46	.91
LDPE	.55	.93
HDPE	.55	.96
PET	.40	1.21