WINDING PROCESS CALIBRATION AND COMPARISON

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INTRODUCTION

Manufacturing of flexible packaging products is a multi-step process, running first through coater-laminators, followed by slitter-rewinders. Each of these steps finishes with winding, hoping to pass on quality rolls to the next process step or final customer.

For many winders, especially older equipment, the process is controlled by setting variables that have limited or no indication of the winding process in engineering units. To recommend changes in winding, the first step is to understand and calibrate the current winder conditions. Knowing ‘as-is’ winding conditions allows for comparing winder-to-winder processes, correlating winding differences to roll defect occurrences, modeling of winding processes (combined with material properties), and engineering-based advice for improved winding.

This paper reviews the calibrating and comparing of winding conditions (tensions, torques, nip loads) across three winders from three different equipment suppliers and how this knowledge was used to improve roll quality.

NOMENCLATURE

r = Radius of the roll, m
w = Width of the roll, m
M_{CTR} = Torque applied by the winder center drive, N-m
T_{CTR} = Force per width of tension created by the center torque drive, N
N_{NIP} = Force per width of nip load, N
T_{WOT} = Total wound-on tension from center torque and nipping, N
μ_K = Kinetic coefficient of friction of product side A to side B
F_{CYL} = Force created by pneumatic cylinders, N
F_{NIP} = Force created by pneumatic cylinders at leveraged nip contact point, N
L_{CYL} = Length from pivot point to pneumatic cylinder connection, m
L_{NIP} = Length from pivot point to nip roller, m
N = Number of pneumatic cylinder

P = Air pressure supplied to pneumatic cylinder, N/m^2
r_{CYL} = Radius of pneumatic cylinder bore, m

BACKGROUND

This winding process audit was arranged to help diagnose a web quality defect that was associated with high pressure near the core. The flexible packaging converter had many years of experience in coating and laminating, but relied heavily on roll hardness testing to diagnose roll quality and process consistency. This winder audit was the first step to help them understand the process variables that control roll hardness, and more importantly, internal roll pressures.

Winding good rolls is a complicated process

Making a good roll is like building a skyscraper. Layer after layer need to be properly placed to form a final structure that meets the roll handling, unwinding, and customer needs. In skyscrapers, we carefully select the land to build on, reinforce it with a solid foundation, and then design progressive levels of the building to support the tens of stories to follow. Imagine if every level of a skyscraper had to be built of the same material? Imagine how a skyscraper reacts to the side load of high winds.

In winding rolls, each layer is made from the same material, yet the layers near the core must withstand the pressures of the many tensioned layers of the roll and do so with less area per wrap than outer layers. In center winding or unwind, rolls have to transmit torque from the bottom layer to the top layer.

Winding is made more complicated by winder design, where equipment design options make a significant different by determining how winding is driven (center-driven, surface-driven, or both), and with center-driven winding whether touch down to the winding roll is controlled by a nipping roller.

Winder control is often an unnecessary barrier to better winding. We know that winding is dependent on torques, tensions, and nip loads exerted by the equipment; however, in many winders, these critical variables are controlled or displayed indirectly.

Imagine if you set a kitchen oven by current (in amps) to the heating coil, but without a thermometer readout. Winding tension is commonly controlled by current to the motor, air pressure to a clutch, or dancer roller weight, without any display of tension (in force or force per width) or torque (in force at radius). Winding nip loads are set by air pressure to the loading air cylinders, without any indication of load in units of force or force per width.

Depending the orientation to gravity, winding nip loads may be independent of weight or complete controlled by it. Many center winder with undriven nips are often oriented to close horizontally with the roller assembly held vertically. This orientation, combined with a near zero or 180-degree wrap angle on the nip roller make nip load independent of gravity and tension. Other winding nips are more complicated.

If a nipping roller presses into the winding roll, then the nip roller assembly weight will contribute to the winding total winding nip load, adding to any additional load from external sources (e.g. air cylinders). If the nip roller closes from above, nip roller weight adds to nip load and has the opposite effect if closing from below. Even more complicated are system where the winding nip roller is held in a fixed position (now usually called a winding drum) and the growing winding roll is pressed into the nip roller with external forces.

In fixed roller winding, nip load is a function of applied load plus or minus the weight of the core, core shaft or chucks, winding support arms, and growing roll weight.

Particularly complicated are winders with pivoting arms that load the core against the winding drum starting at starting angle (usually 45-degrees), but the trigonometry of the winding changes as a function of roll size.

Winder Calibration

To better understand any winding processes, the first step is to review the type of winding equipment. The second step is to calibrate or estimate the winder to understand how the critical variables are controlled. Two main variables must be determined for any winder. Tension and nip load at the outer radius of the winding roll as a function of roll radius. With this understanding in place, winding conditions can be compared and correlated to roll and web defects to determine if winding changes may reduce or remedy the defects.

In this winding process audit, the goal was to understand how three winders control roll tightness through tension and nip load, specifically the winding conditions of end of a triplex laminating line (Winder NM), a slitter-rewinder (Winder EM), and duplex laminating line (Winder CO).

Winding tension is commonly displayed in engineering units. Many center winders have closed-loop tension control with center torque is response to either a force loaded dancer roller or force-measuring load cell roller. Load cell rollers (a.k.a. tension rollers) provide direct feedback of web tension force, but should be ensured for proper calibration.

Dancer rollers create a constant load into the web, limiting the force created by center torque, but may also introduce tension variations if they have significant drag, inertia, or geometry changes. Many dancer roller system will be controlled remotely with an I/P transducer, adjusting current to change pressure to an pneumatic cylinder, increasing or decreasing the force applied to the web, often changing on a tapering function versus growing roll radius. These dancer systems will commonly be set by entering a tension set point (and taper percentage), but do not provide feedback of actual tension. If combined with a load cell roller in the same zone, the dancer performance can be monitored. For winders controlled by a dancer roller without accompanying load cell rollers, winding tension from dancer roller should be estimated or verified to allow trust in the displayed tension values.

Not all winders have center torque under the closed-loop control of a dancer or load cell roller. Many slitter rewinders use pneumatic differential slip shafts where air pressure is supplied to create a frictional clutch via radial or axial load against the winding roll. Some winders have open-loop torque controlled motors. In our winder audit, the Winder EM winding torque was controlled by pneumatic clutch. In each of these open-loop torque controlled winding cases, some estimate or measurement is required to determine the tension created by the center torque.

Nip loads are rarely defined in engineering units of force or force per width, instead adjusted with a simple pressure regulator, providing the vague notion of more or less nip load, but leaving vague and undetermined the relationship of nip load as a function of pressure.

In our winder audit, the three winders were controlled as outlined in Figure 1. Nip loads for any winder can be easily estimated from the nip assembly design. First, calculate the effective force created by the system air cylinder. Then, calculate the effective load at the point of winding due to mechanical advantage or disadvantage of the pivot system.

$$F_{CYL} = nPA = nP(\pi r_{CYL}^2) \quad \{1\}$$

$$F_{NIP} = F_{CYL}\left(\frac{L_{CYL}}{L_{NIP}}\right) \qquad \{2\}$$

Winder	Tension	Nip Load
Winder NM	Dancer controlled center winder with load cell roller tension measurement. Taper tension displayed in percent, limited to 0 to 50%.	Air pressure regulator to horizontally controlled pivoting nip roller (share between two positions on a turret winder).
Winder EM	Combined center-surface winder. Center torque controlled air pressure to pneumatic slip clutch. Constant torque winding.	Winding roll nipped to central surface drum with changing nip geometry as roller diameter increase.
Winder CO	Dancer controlled center winder with load cell roller tension measurement. Linear taper tension set to decrease 25% at final 1m diameter.	Nip load was set by the system, accounting for roller weight, as both a starting nip load and linear taper.

Figure 1 – Comparison of Tension and Nip Control by Winder

Winder	Tension	Nip Load
Winder NM	Winding tension started at the core with 38 kgf, tapering down 45% to 21 kgf at the final diameter or divided by 0.75m width, tapering from 50 to 28 kgf/m.	Nip force was estimated as a constant 50kgf (from the nipping roller pivoting geometry and air cylinder size). For web side A/B COF of 0.3, T_{NIP} is 15 kgf over 0.75m width or 20 kgf/m.
Winder EM	Calibration of the pneumatic winding clutch was determined using a force gauge to measure the force at the core and with a finished roll to slip the clutch as a function of pressure. (More details below.)	Nip load was estimated from geometry of the starting core and final roll nipping geometry, including air pressure and roll weight. (More details below.)
Winder CO	Winding tension started at the core with 12 kgf, tapering down 25% to 9 kgf at the final diameter or divided by 0.75m width, tapering from 16 to 12 kgf/m.	Similar to winding tension, nip load started at the core with 12 kgf, tapering down 25% to 9 kgf at the final diameter or divided by 0.75m width, tapering from 16 to 12 kgf/m.

Figure 2 – Winding Tension and Nip Loads by Winder

For Winder EM, a handheld force gauge was used to calibrate the pressure to torque function. The force gauge was attached to the core and the force to slip the pneumatic clutch was measured as a function of pressure. To measure higher torque conditions, additional measurements were taken by placing a finished roll in the winding position and measuring the force to slip from the larger radius of the finished roll. In both cases, the measure force was multiplied by radius to calculate torque.

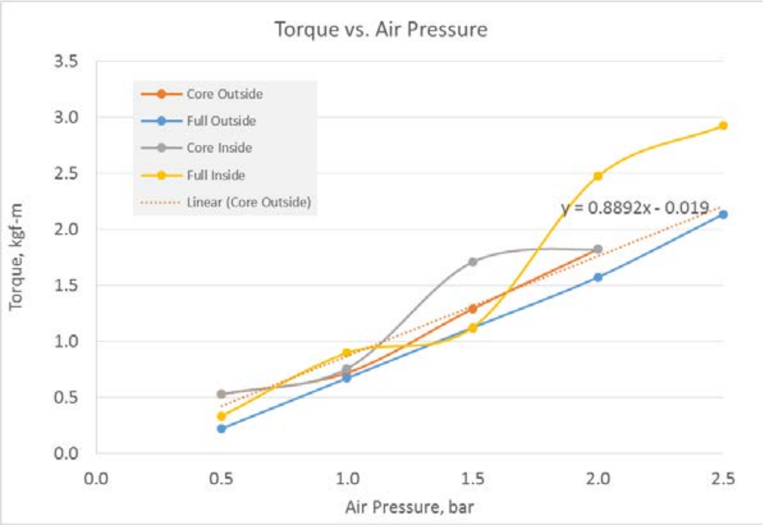

Figure 3 – Calibration of Winder EM Torque vs Supply Pressure

The nip of Winder EM was controlled by the effective nipping of the roll weight (including the rewind arms) and the added or counter-balancing force from the air cylinders. The roll weight offset function of Winder EM broken, so nip load increased as roll size and weight increased. The nip load was estimated from the start and end of winding from a force gauge measurement of the core and rewind arm, large diameter roll weight, and the nipping geometry at core and large roll diameter. For ease of calculations, a linear function was used to estimate the nip load between the core and final roll diameters.

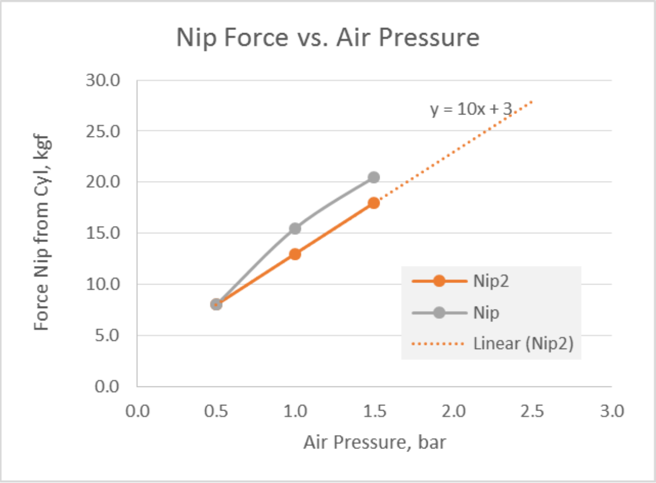

Figure 4 – Calibration of Winder EM Nip Force vs Supply Pressure

Winder Comparison

The simple model for wound-on tension (WOT) of a center winder with a nip roller is a function of entering web tension and nip-induced tension, here expressed in units of force per width[1] {1}. For surface winders, a simplified model (for nip load under 1750N/m) describes wound-on tension as independent of upstream web handling tension and solely a function of nip load and product friction. If the web tension component is replace with center torque divided by radius and width, one equation can be used to describe center winding with or without a nip roller and surface winding {2}.

$$T_{WOT} = T_{WH} + \mu_K N_{NIP} \qquad \{3\}$$

$$T_{WOT} = \frac{M_{CTR}}{rw} + \mu_K N_{NIP} \qquad \{4\}$$

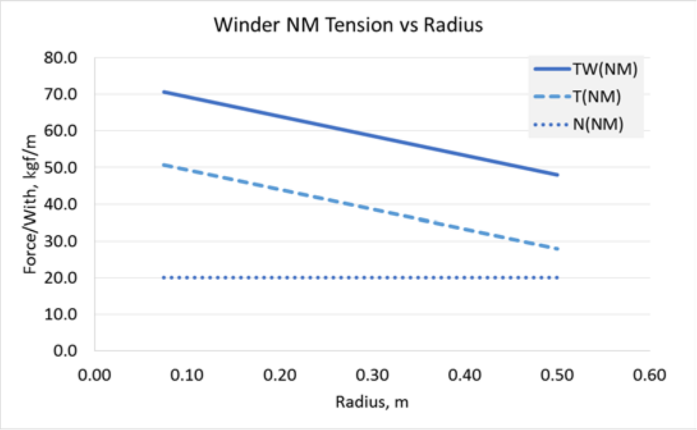

Figure 5 – Winder NM Wound-On Tension from Torque and Nip

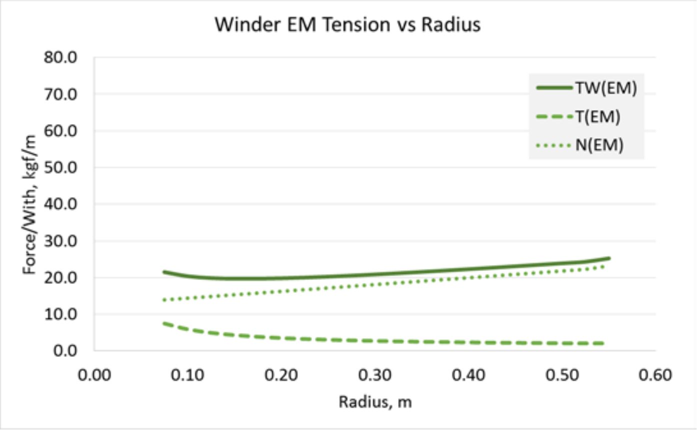

Figure 6 – Winder EM Wound-On Tension from Torque and Nip

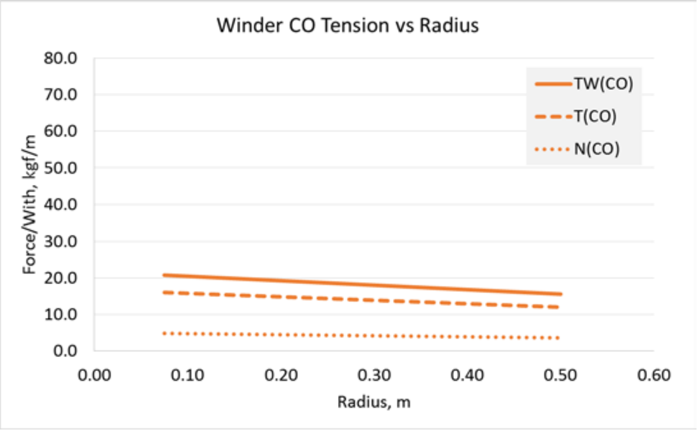

Figure 7 – Winder CO Wound-On Tension from Torque and Nip

Estimates wound-on tension as a function of tension or center torque and nip load was determined for each of the three winders. The scale on the following graphs are fixed to allow visual comparison between the winders. Winder EM creates most of its wound-on tension from nip-induced tension. Winder CO creates most of its wound-on tension from center torque.

Total Winding Tension. Winder NM and CO are center winders with undriven nipped rollers. Winder EM has center-surface winding. Qinder NM is set to wind with significantly higher tension (from the combination of center torque and nip load) that Winders EM or CO. The following graphs compare the total winding tension (from torque and nip load), the separate components of winding tension from torque and tension from nip load, also center torque for the three audited winders.

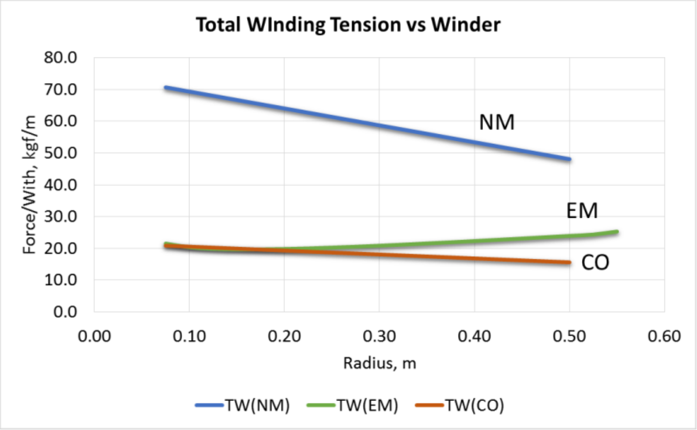

Figure 8 – Comparison of Wound-On Tensions

The primary difference in these two winders is the relationship of pre-winding tension on roll tightness as controlled by center torque and nip load. In center winding, pre-winding tension is controlled by center torque, making pre-winding tension (controlled by dancer load and position, measured by the load cell roller) an important winding variable. In center-surface winding, pre-winding tension is largely controlled and isolated from center torque by the surface driven roller, making pre-winding tension nearly insignificant to roll tightness. In the case of center-surface winding, center torque needs to be determined independent of pre-winding tension.

Center Torque. Winder NM applies the highest center torques at winding and the highest torque increase. Winder NM was also artificially constrained in taper tension as its programming only allows linear taper tension and limited the maximum taper tension to 50%.

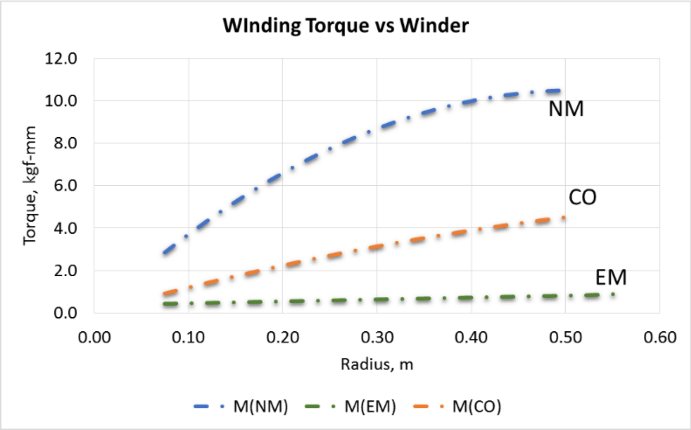

Figure 9 – Comparison of Winding Torques

Winder CO has the highest torque change with final torque 5x starting torque. Winder NM has the highest final torque, though the start to final torque ratio was only 3.7:1. Winder EM has the most modest torque increase, only 2:1.

The high torque increase on Winder NM contributes to the cinching (internal roll machine direction slippage) and cinching-enabled telescoping. In Figure X, a spoke line was drawn after winding 75mm of roll buildup. In adding 50mm more to the roll buildup, the first 40mm above the core cinched (curved line on layer inside the dashed ring).

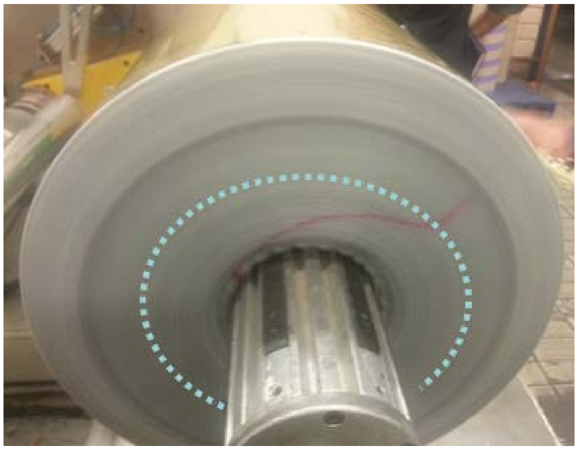

Figure 10 – Cinching Revealed from Spoke Line Test

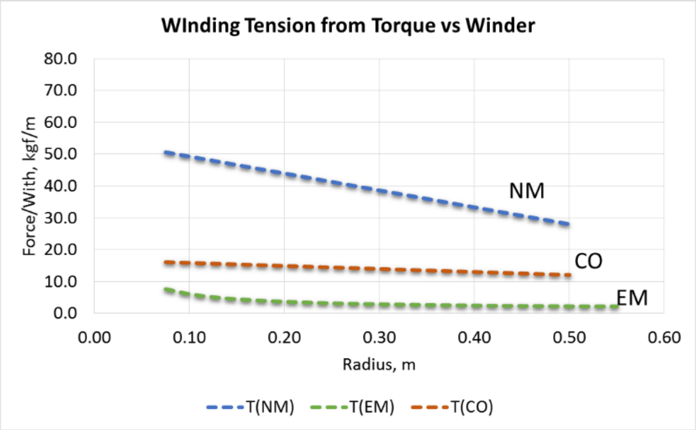

Figure 11 – Comparison of Tension from Torque

<u>Tension from Torque.</u> The three winders had gross different levels of winding tension. Winder NM had tension over three times as high as Winder CO, though winding similar products. Winder EM had the least tension from center torque, likely set to compensate for its artificially high nip load (see comments below).

<u>Nip Load.</u> Winder EM creates most of its roll tightness through nip load, with much of this created by roll weight. As the roll increases in diameter its increasing weight create higher nip load, making the winding nip load ‘reverse’ taper (increasing tension with roll radius). Reverse taper is never recommended, as it creates a roll with less interlayer pressure near the core than constant tension or conventional decreasing taper. Less roll tightness near the core makes rolls that are more likely to have shifted layers in roll handling, cinching at unwinding, and increase chance of starring and transverse direction buckling defects (a.k.a. cross-buckles).

Reverse taper is especially troublesome when roll tightness is judged with roll hardness. Roll hardness mostly measure the condition at the end of winding. Two roll end at the same tension would have the same roll hardness, but if one was reverse tapering, it would be more prone to the shifting, cinching, starring, and buckling.

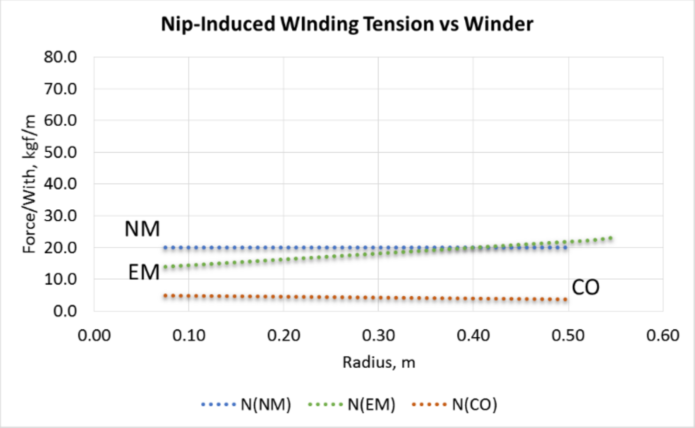

Figure 12 – Comparison of Nip-Induced Tensions

Recommendations

Winder NM needs to have a tension taper function programming change to allow cinch-free winding. Winder NM should be upgraded by the supplier or a controls engineering contractor to provide a choice of taper function (either tension linear with radius or torque linear with radius) and change the taper limit to allow constant torque winding or up to 80% linear taper. To reduce cinching and cinching-induced telescoping, complete winding trials with a torque-based tension taper with approximately 2X torque increase during winding. Increase nip load to offset roll hardness or tightness lost from center torque is decreases as needed.

Winder EM has a roll weight offset function, but the controls were broken, due to an I/P transducer failure. The roll weight offset should be fixed to allow winding with traditional taper tension.

Roll hardness measurements should be supplemented with understanding and insights gained from this winder audit and comparison.

With winder calibration completed, only a few web property measurements (e.g. stack modulus) are required to take the next step of modeling the pressures within the wound rolls. The combination of winder calibration, roll pressure models, and experimets to correlate to high pressure defects should allow winding process optimization more efficiently than the past practice of relying roll hardness and indirect process variables.

ACKNOWLEDGMENTS

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REFERENCES

1. Good, J. K., Roisum, D. R., Winding: Machines, Mechanics, and Measurements, TAPPI Press, 2008, p.192.