MODELLING A CHILLED CAST THERMO ROLL UTILISING ULTRASONIC MEASUREMENT

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Abstract: *This paper discusses the creation of a chilled cast iron thermo roll model. The model can be used to analyse the behaviour of a thermo roll under different operating conditions, e.g. operating temperatures or rotating speeds. Ultrasonic measurements of a full-size roll were made to acquire additional information about the internal structure and dimensions of the roll shell. The layer structure of a chilled cast iron roll body was measured for the first time. The shapes and dimensions of the roll model that was created correspond well to the general knowledge about chilled cast iron thermo rolls. Validation of the model is the next research step.*

Key words: *paper machine, calender, thermal deformation, peripheral bore, ultrasound*

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1. Introduction

For many decades chilled cast iron thermo rolls have been successfully used in the calenders of paper machines. In 2004 the proportion of chilled cast iron thermo rolls amounted to 99% of all the thermo rolls in the paper industry (SHW, 2004). Even though the number of forged steel thermo rolls and other thermo roll types is slowly increasing, the number of chilled cast thermo rolls is still dominant. Chilled cast iron has been used for roll shell material mainly because of its good manufacturability and low material cost. Thermo rolls have an undesired tendency to deflect when heated to their operating temperature. This temperature-dependent deflection is also called thermal bending. Because of the properties of the cast iron roll body, chilled cast thermo rolls are more prone to this phenomenon than other roll types. A better understanding of this phenomenon is needed. This study discusses the creation of a thermo roll model to be used in future simulations of the behaviour of these rolls.

Fig. 1. Different thermo roll types: a) centre bore roll; b) displacer type roll, and c) peripherally drilled roll (Jokio, 1999).

There are several types of thermo rolls and the most common are centre bore rolls, displacer type rolls, and peripherally drilled rolls. The working principle of these thermo rolls is based on hot heating fluid flowing through the roll body, i.e. the roll is heated from inside. Modern thermo rolls are mainly peripherally drilled rolls or displacer type rolls. The focus of this study is on peripherally drilled chilled cast iron thermo rolls. (Jokio, 1999; Wirtz, 2002)

The roll body is cast in a stackable chill mould, usually with a sand core. The cooling of the roll body casting can take days or weeks. The casting and manufacturing process of chilled cast thermo rolls is discussed in detail in the dissertation of Maijer (1998). The rolls studied in the dissertation are similar to the roll used in this study.

Fig. 2. Different layers of iron in the chilled cast iron roll shell and their content as a function of depth (Jackot et al., 2000; Wirtz, 2002).

The chilled cast iron roll body has different iron layers. The thickness and the microstructure of these layers are a function of temperature and time during the casting and cooling process (Maijer, 1998; Seah et al., 1998; Jackot et al., 2000). The outer surface layer consists mainly of white iron (also known as the chill layer, chill iron, or white cast iron). This layer has a microstructure consisting of iron carbide (cementite) embedded in a matrix of pearlite. Moving towards the inner diameter, the microstructure shifts to an equilibrium grey iron microstructure (also known as grey cast iron), comprised of flake graphite particles in a pearlite matrix. The microstructure in the transition zone is referred to as being mottled, and thus it is named mottle iron (Fig. 2).

The thickness of the white iron layer on the surface is typically 8 to 24 mm in paper machine rolls (D'Amato, 1987; Zwart & Farrel, 1992). This layer gives the roll surface the required hardness and wear resistance. The grey iron inner layer is shock-resistant. The layer borders do not have a clear edge (Fig. 2). The thicknesses of the layers can be measured visually (also under a microscope after etching) and/or by hardness measurement from the end faces of the roll body.

The layers in the roll shell have a different iron phase, and thus have different material values, i.e. hardness, thermal conductance, coefficients of thermal expansion, density, and elastic modulus. The layers can have an asymmetrical arrangement as a result of their varying thicknesses. When such a roll is heated it can act like a bi-metal rod and deflect (Fig. 3). The thermal deformation of the thermo roll is caused by the different thermal expansion coefficients of the iron layers and/or uneven temperature distribution in the roll body. The deflection, if caused by the uneven layer thickness, takes place in the direction where the thickness of the white iron layer has its local minimum (SHW, 2005). Other thermal deformations are also possible. Because of these deformations, a thermo roll that has practically no run-out at room temperature can have a significant run-out at its operating temperature. (Brierley et al., 1977; Rothenbacher & Vomhoff, 1985; Wirtz, 2002; Kiviluoma, 2009)

Fig. 3. Measured run-out of: a) deflected thermo roll; b) S-shaped thermo roll in a paper machine under normal production conditions and temperatures (Pirttiniemi et al., 2009).

Fig. 4. Two buckled roll castings in their chill moulds and the machined roll bodies.

The varying thicknesses of the layers are a result of the casting process (US 005915890, 1999; US 007481754B2, 2009). The roll casting shrinks during cooling more than the chill mould, thus partly releasing itself from the mould wall. In this stage only the surface of the casting is solidified, while the bulk is still molten. Because of this the casting can buckle (Fig. 4, left-hand sides). The partly solidified outer layer is mainly white iron and keeps its phase during the cooling period. When the roll casting is machined, it has a white iron layer on the outer surface that has a varying thickness (Fig. 4, right-hand sides).

1.1 Peripheral bores

Peripherally drilled rolls usually have 15 to 50 bores which are 20 to 60 mm from the roll surface. The diameters of these bores are 25 to 50 mm (Jokio, 1999). The length of the bores is the same as the length of the roll body, i.e. up to 12 m. The drilling is normally performed from both ends of the roll body and the bores meet in the middle of the roll. An overlap of the bores is used to ensure the unrestricted flow of the fluid in the passage. Small meeting errors are common (Fig. 5).

Fig. 5. Meeting error of the bores of a fluid passage in a thermo roll body.

In long bores there is another phenomenon that sometimes causes unwanted behaviour or difficulties in the manufacturing of the rolls. Because the boring rod has a relatively small diameter compared with its length, it will sag when drilling deep bores (Fig. 6). The sag of the rod, together with the non-homogeneous material in the roll body, also causes variation in the axial depths of the passages. This variation can be the cause of an uneven temperature distribution and thermal deformations in the roll, as mentioned above. If large enough, the variation can be the source of an uneven mass distribution, thus causing an unbalance in the roll. (Rothenbacher & Vomhoff, 1985; Wirtz, 2002; Zaoralek, 2004)

Fig. 6. Change in the drilling direction as a result of the sag of the boring rod.

There are many designs for the heating fluid passages, ranging from one bore per pass to three or more adjacent bores (Grosskreutz, 2010). The heating fluids used with thermo rolls are water, steam, or thermal oil. When the heating fluid flows in the passages, it releases some of its heat to the roll and becomes cooler. This causes a temperature drop between the beginning and the end of the passage.

This study discusses the creation of a chilled cast iron thermo roll body model. Ultrasonic measurements are used to acquire the dimensions of the peripherally drilled bores in the shell of the roll body. Ultrasound is also used in measuring the layer thickness of the white iron layer on the roll surface. The dimensions of these are normally not measurable by normal workshop measuring devices.

2. Methods

In this study a chilled cast iron thermo roll was used as a basis for a set of roll models. The thermo roll was the upper roll of a soft calender (Fig. 7). The dimensions of the roll are given in Table 1. The heating passage design was duo-pass with 40 peripheral bores. The heating fluid was thermal oil.

Fig. 7. The thermo roll that was studied is the upper roll of a soft calender.

Total length	9810 mm
Body length	7690 mm
Max. paper web width	6660 mm
Nominal diameter	1067 mm
Shell thickness of the roll body	198 mm
Bearing length	8400 mm
Peripheral bore diameter	32 mm
Layer thickness of white iron	9 mm
Layer thickness of mottle iron	42 mm

Tab. 1. Test roll dimensions according to technical drawing and manufacturer.

The test roll was measured with an ultrasound measuring device during maintenance. These measurements were carried out on a roll grinder at a roll shop. They are discussed in the next chapter.

2.1 Ultrasonic measurement of the white iron layer

The ultrasonic wall thickness measurement is based on the time of flight measurement. The time of flight (ToF) is measured from the ultrasonic pulse echoes at the interfaces, e.g. the outer and inner surfaces of a tube. For it to be possible to calculate the thickness, the speed of sound in the material must be known (see Equation 1). The speed of sound has a different value in the different layers of cast iron, thus making the normal ultrasonic shell thickness measurement of cast iron objects difficult. When the shell thickness of the roll body is measured, a variation is observed. The cause of this variation may be the uneven distribution of the iron layers or an actual variation in thickness. Therefore, ultrasound cannot be used for the thickness measurement of cast iron objects with an unknown content of white and

grey iron. As the thickness of the shell of the thermo roll body is normally known and the actual variation in thickness is small, the variation in the ultrasonic shell measurement can be used to calculate the layer thickness distribution if the speeds of sound in the different layers are known.

IF : Interface echo
BE : Backwall echo
 c : Speed of sound

Fig. 8. Left: principle of the ultrasonic shell thickness measurement. Right: ultrasound probe (circled) and its support on a grinding machine.

The shell thickness of the test thermo roll was measured with an ultrasonic measuring device that was developed (Fig. 8) (Uski, 1999). The measurement was carried out in a roll grinder and the whole roll body was measured in a single helical measurement.

Fig. 9. The simplified roll shell layer structure in the model (above) and normal layer structure of the thermo roll shell (below).

To simplify the calculations, it was assumed that one half of the mottle iron layer behaves like grey iron and the other half like white iron (Fig. 9), so the roll could be treated as an object with two layers. The thickness of the roll shell when measured with ultrasound is calculated as follows:

$$s_m = t_m c_m, \quad (1)$$

where:

- s_m measured thickness,
- t_m measured ToF, and
- c_m speed of sound used in measurement.

Because the roll shell is treated like a two-layer object, a more accurate estimate of the ultrasound measurement of the thickness is:

$$s = s_w + s_g = t_w c_w + t_g c_g, \quad (2)$$

where:

- s total thickness,
- s_g thickness of the grey iron layer,
- s_w thickness of the white iron layer,
- t_g ToF in grey iron,
- t_w ToF in white iron,
- c_g speed of sound in grey iron, and
- c_w speed of sound in white iron.

The unknown values are s_g , s_w , t_g , and t_w . It is possible to calculate s_g and s_w if t_g and t_w are known. The following equation is also true:

$$t_m = t_g + t_w. \quad (3)$$

The unknowns from Equations (2) and (3) can be solved if the total thickness s of the roll shell is known:

$$t_w = \frac{t_m c_g - s}{c_g - c_w} \text{ and} \quad (4)$$

$$t_g = t_m - t_w. \quad (5)$$

When the Equations 4 and 5 are combined with Equations 1 and 2 then the thicknesses of the layers can be calculated by the equations:

$$s_w = t_w c_w = \frac{c_w}{c_g - c_g} (s - s_m \frac{c_g}{c_m}) \text{ and} \quad (6)$$

$$s_g = s - s_w. \quad (7)$$

The problem when using Equations 6 and 7 is that the actual speed of sound in the roll body is not known. Neither is it a constant, but a function of the depth in the roll body. In Fig. 10 this is shown as a function between the actual depth and the measured depth. This function gives the relations between the speeds of sound that are needed and the speed of sound used in the measurement. From the relations the values can be solved. Because the relations are assumed to be constant, they can be calculated from the known points. The first point (x_0, y_0) is the outer surface, where the measured and the actual values are both zero. The second point (x_2, y_2) is the inner surface of the roll body. The actual thickness of the shell is given in the technical drawing. The measured value can be acquired with the ultrasonic measuring device. The third point (x_b, y_b) is the depth of the bores in the roll body ends. There their depth can also be measured with the ultrasonic device. From the point (x_w, y_w) of the layer border only the actual value is known. It can be calculated from the thickness of the white iron layer and mottle iron layer, because the roll body is treated like an object with two layers (Fig. 9). The actual layer thickness of white iron is 9 mm and half of the mottle iron is $42 \text{ mm}/2 = 21 \text{ mm}$, thus giving for $x_w = (9+21) \text{ mm} = 30 \text{ mm}$. The depth of the measured layer border (y_w) can be solved from the constant relations. All the points are listed in Table 2. The solved value for y_w is also given.

Fig. 10. Relation between the measured depth and actual depth in the case of two layers. An estimate of the actual relation is also given.

Point	x-value [mm]	y-value [mm]
x_0, y_0	0.0	0.0
x_w, y_w	30.0	(14.9)
x_b, y_b	68.5	53.9
x_2, y_2	198.0	184.9

Tab. 2. The points from Fig. 10. The values are from the roll end. The x-values are actual values and the y-values are measured values, except y_w , which is solved.

The equations to solve the relation (slope ratio) are:

$$k_w = \frac{y_w}{x_w} \text{ and} \quad (8)$$

$$k_g = \frac{y_2 - y_b}{x_2 - x_b}, \quad (9)$$

where:

k_w slope ratio for the white iron part, and
 k_g slope ratio for the grey iron part.

The equation to calculate the speed of sound with the help of the relation is:

$$c_x = k_x c_m, \quad (10)$$

where:

c_m speed of sound used in measurement,
 k_x slope ratio of the material (k_g or k_w), and
 c_x speed of sound of the material (c_g or c_w).

Another way to obtain the speed of sound would be to calculate it from the material values. Equation 11 gives the speed of sound if the material values are known (Kinsler et al., 1999):

$$c_l = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}, \quad (11)$$

where:

c_l speed of sound,
 E elastic modulus,
 ρ density, and
 ν Poisson's ratio.

Material	E [GPa]	ν	ρ [kgm ⁻³]
White iron	180	0.27	7694
Mottle iron	140	0.27	7583
Grey iron	120	0.27	7334

Tab. 3. Typical material values of the iron phases. (Brierley et al. 1977; Zwart & Farrel, 1992; Jackot et al. 2000; Wirtz, 2002)

The speeds of sound were calculated with Equation 11. The material values used in the calculations are presented in Table 3. The values for the speeds of sound are presented in Table 4.

Material	Solved from measurement data	Calculated with Equation 11	Literature	Measurement software
White iron	9230	5406	$> c_g$	-
Mottle iron	-	4803	$> c_g$	-
Grey iron	4549	4522	3500 - 5600	4600

Tab. 4. Speed of sound [ms^{-1}] in cast iron

The calculated value for grey iron (c_g) solved from the roll body ultrasound measurement is close to the value used in the measurement and close to the calculated value from the equation. This value can be considered to be close to the actual value, as it is solved from two measurements entirely inside the grey iron layer.

The solved speed of sound value for white iron (c_w) is very high, much higher than any value found in the literature for iron-based materials. The solved value for c_w is dependent on the location of the point (x_w , y_w). The too-high value for c_w means that the actual location of the point (x_w , y_w) should be further right and further up in the graph. One reason for the high value is that the speed of sound also varies inside the grey iron layer, being higher close to the transition zone (Fig. 10). This gives an impression of a thicker white iron layer. The missing mottle iron layer also explains some of the increase in the c_w value. The true relation is estimated in Fig. 10. So, despite the fact that the c_w value is disputable for white iron, it is used in this work.

2.2 Ultrasonic measurement of the peripheral bores

The peripheral bores in the roll were also measured with the same ultrasonic measurement device that was used for the roll shell thickness measurement. The data in the map of the bores contained depth values which could not be used (between the bores) and some measurement errors. Because of this the data were filtered and converted to the centrelines of the bores by the software explained in the next chapter. The software used averaging, elimination, and polynomial fitting in the filtering procedure.

The ends of the bore centrelines were adjusted to known depth values taken from the technical drawing of the roll. This adjustment was performed to correct the depth error in the bore measurement caused by the white iron layer. On the basis of the calculated layer map, a total correction of the centrelines would have been possible, but it was estimated that the deviation between the chosen adjustment and the total correction would have been less than 3 mm. This deviation was considered to be small enough to be negligible in the future use of the model.

2.3 The model of the thermo roll

The roll model was created from the dimensions of the test thermo roll (Fig. 7). The dimensions of the peripheral bores and the layer thickness of white iron, which were not present in the drawing, were measured with ultrasound as described previously. A program was developed to convert the ultrasound measurement data into a form that can be read by CAE software. The program that was developed filtered the measurement data, removed unwanted results (results between the bores in the bore measurement and results from the bores in the layer measurement), and converted the shell thickness data into a surface of the layer border and the bore depth data into bore centrelines. It stored the surface geometry of the layer border into a STEP file. The bore centrelines were stored in another STEP file. The STEP data format is explained in the ISO 10303 standard (1994). In the software additional parameters could be adjusted to influence the filtering and model creation procedure.

Fig. 11. Modelling steps and software used in the creation of the roll model

In Fig. 11. the modelling steps and software used in the procedure for the creation of the model are shown. All other software except the ultrasonic measurement software and CAE software was programmed by the research group. The ultrasonic measurement software was provided by the ultrasonic device manufacturer. The CAE software that was used was Pro/Engineer from Ptc Ltd.

3. Results

3.1 Layer border

The thickness of the layers of the roll body was measured with the ultra-sound measuring device. The thickness data contained 270,468 (66x4098) measured values. The average thickness was 184.9 mm and the maximum deviation from the average was approx. ± 2.0 mm. With Equations 6 and 7 and the solved speeds of sound it is possible to calculate the thickness distribution of the white iron layer in the roll. The layer distribution was calculated with computer software and the result is presented in Fig. 12. The thickness of the white iron layer varied from 27.0 to 33.3 mm in the calculated data. The average thickness of the layer was 30.3 mm. The average thickness value amounted to more than 30 mm, because the points for the speed of sound function were taken from the end of the roll body. There the calculated thickness had an average value of 30 mm.

Fig. 12. The white iron layer thickness data created from the measured ultrasonic shell thickness data. The values at the contour lines are thickness values in [mm].

Fig. 13. The centreline offset and phase of the layer border.

The centre point of each cross-section of the border of the layer was compared to the centreline of the roll. The offset and the direction from the centreline of the roll

were plotted along the axial position. This corresponds to the centreline of imaginary circles drawn through the white iron layer. They were calculated using FFT from all the cross-sections of the layer thickness data. The amplitude and phase of the first FFT term (first harmonic component) of each cross-section correspond to the offset and the direction from the centreline of the roll. The centreline offsets and their directions are shown in Fig. 13. From the centreline the original buckling of the roll body in the mould can be estimated.

3.2 Peripheral bores

The depths of the peripheral bores were also measured. The result data contained 986,400 (240x4110) unfiltered depth values. From the data some meeting difficulties in the bores and some scattering in the bore depths similar to the result found in the literature (Zaoralek, 2004) were seen. The depth data cannot be used directly for the creation of a model of the roll, and thus the data were filtered and the end areas were adjusted to known depth values. The depth values are taken from the technical drawing and are located in the end areas of the roll body. The results are presented in Fig. 14. From the result data the model for the bores was created. The details of this model will be discussed in the next chapter.

Fig. 14. Bore depths of all the bores (1 to 40) in the roll body (upper figure). The worst and the best meeting of the bores (lower figure). The depth value is the distance of the centreline of the peripheral bore from the surface.

3.3 The roll body model

The white and grey iron layer models were created from the ultrasonic shell thickness measurement with Equations 6 and 7. In order to simplify the model, the roll shell was treated like a body with two layers, so there was no mottle iron layer in the model. The solved layer thickness data (Fig. 12) were converted to a surface model and stored in a STEP file. From the surface two solids were created. The surface became the inner surface of the white iron solid and the outer surface of the grey iron solid.

Fig. 15. The cut-out bore model.

Fig. 16. The roll body model from two angles. The extra holes in the roll end are the holes for the fastening bolts for the journals.

From the bore data (Fig. 14) a STEP file with the centrelines of the bores was created. Each centreline was used as the trajectory of a protrusion. The protruded section was a circle with a diameter of 32 mm. The solid that was created, with 40 protrusions (Fig. 15), was used to cut the peripheral bores into the grey iron solid. In the model of the roll body the white and grey iron models were combined (Fig. 16).

4. Discussion

The method that was developed gives rise to the possibility of modelling the roll body of a chilled cast iron thermo roll in detail for the first time. The layer borders and peripheral bores were measured and the model was created on the basis

of the measurements. The shapes and dimension of the model correspond to the general knowledge about chilled cast iron thermo rolls. To validate the measured dimensions is challenging, because the only known method to validate them (especially the layer thicknesses) is to cut the roll into small pieces and to measure the dimensions from the pieces. The roll is too large to fit inside an X-ray or another non-destructive measuring device. Smaller test rolls and/or cooperation with the roll manufacturer can provide a solution to this problem. A roll that is at the end of its life span could also be used as a test roll to verify the layer measurement method.

The measured shell thickness of the roll showed a variation of approx. ± 2 mm. According to the manufacturer, the variation in thickness after machining is below 0.3 mm. So the measured variation in thickness can be assumed to represent mainly the layer variation. The shape of the centreline (Fig. 13) of the modelled layer border also corresponds well to the buckled roll body presented in Fig. 4. The measured peripheral bores are very similar to the bore hole measurement results in the article by Zaoralek (2004). Manual ultrasound measurements of the individual bores can be used to check the calculated result. If the journal or both journals of the thermo roll can be removed, the depths of the bores and the thickness of the iron layers can be verified in the end areas of the roll body. At the same time a calibration of the method can be performed.

The major difference between the model and the roll is in the layer structure. The model contains only two layers but the roll has three layers. Additionally, the layer borders are sharp in the model, which is not the case in reality. The iron phase content in the layers changes smoothly as a function of the depth, and thus modelling the real layer structure is challenging. If the model is used in a finite element analysis, then the changing layer material properties can be simulated with user-supplied functions, but this discussion is beyond the scope of this study.

If the model is used in simulations, the measured dimensions can be partly validated if the simulated behaviour correlates to a measured behaviour, e.g. thermal bending or bending caused by the centrifugal forces. For the simulation, e.g. structural analysis, all the necessary material parameters should be acquired from the literature, or preferably, be measured directly from the roll material.

5. Conclusion

Ultrasonic measurement of the cast iron thermo roll was put into practice. The model was created from the dimensions of the test roll. It was complemented with the measured dimensions of the peripheral bores and layer thickness. The modelled geometry of the layer border in the roll body was congruent with the shape caused by the buckling of the roll casting in the chill mould.

The model gives actual information on an already existing thermo roll. This information can be used for simulating the behaviour of the thermo roll to achieve a more accurate manufacturing process, find ways to tackle the thermal bending, and also to improve the maintenance procedure of thermo rolls.

The next step in this research is to verify and validate the model. There are two paths that can be followed simultaneously or separately. One is based on validating the measured values by new measurements on the roll. The other path is to use the model for simulations and compare the simulated behaviour to the actual roll behaviour. The first path will be hard to follow, as permission to dismantle the roll journals is very likely to be denied. The validation of the future simulation results requires only measurements of the roll in its current condition. Therefore the approval for this is more probable.

If the validation can be performed successfully, then the model can be used to test different available thermal bending reduction methods on the model. Normally, the application of the reduction methods is time-consuming and requires modifications to the roll, sometimes irreversible ones. If the best reduction method can be chosen with the help of simulations, this saves costs and time. Even if the validation of the model cannot be performed, it can be used to study and simulate phenomena in thermo rolls in general, because the structure and the dimensions of the model mainly correspond with those of actual thermo rolls.

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