GUIDELINES FOR ALLOWABLE IN-PLANE ROLLER MISALIGNMENT USING WRINKLING AND WEB BREAK MODELS

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ABSTRACT

While we have had wrinkling and web break models for a quarter century and the means for precision roller alignment for a half century, no consistent recommendations have been made as to allowable tolerances for roller misalignment. The lack of consistency is not so much due to variability of web properties or web machine specifics. Rather, it is mostly due to cultural reasons. The paper industry typically specifies what it *could* do rather than necessarily what it *should* do and is a fraction of one hair's breadth for dry end equipment. The converting industry, in contrast, is largely silent on the subject of alignment and thus leaves it to every individual involved to figure out or, more likely, guess at what needs to be done.

This paper proposes guidelines for allowable in-plane roller misalignment, the more critical of the two directions, based on well-tested wrinkling and web break models. The wrinkling criteria is lack of wrinkles crossing a roller at any value of tension. The web break criteria is limiting maximum tension (at the outside of the bend) to twice the average and thus keep the inside of the bend from going into compression. For those who do not wish to use models, an experimental technique to obtained allowable in-plane misalignment is also described. For those who do not wish to use either models or experiment, a set of quality classes is described that captures best practices in some of the more common web applications.

This paper also includes a few parametric studies revolving around some of the more common materials such as paper and thin films that will show what sensitivities are important and what might be safely ignored. All of this is aimed at what *should* be done, i.e., when *should* a roller be moved. Finally, a brief review of alignment methods and tools describe what we *could* do in a commercial setting. In other words how close can we expect roller alignment to get *when* we choose to move a roller.

ORIGINS OF PRECISION ROLLER ALIGNMENT

References to web machine alignment are at least one century old [1]. In this paper, however, we will refer only to precision methods that are capable of accuracies on the order of one hair's thickness (125 microns or 5 mils). Certainly **hand tools**, such as dial indicators, are able to *occasionally* reach these precisions in limited circumstances such as for merely obtaining in-plane parallelism between a pair of rollers. However, hand tools are not able to do a 'full' alignment that consists of three elements: level, square and common centerlines. Instead, we will begin with **optical tooling** that is the centerpiece of the earliest precision methods and the one that is still the most common even today.

By optical tooling we mean instruments resembling the surveyor's precision sight level and theodolite that you often seen on building construction sites, lot mapping and roadways. However, there are a few distinctions. The first is that while precision levels and theodolites can be used, the primary tool that the web alignment crew will use for squaring rollers to an offset centerline is the TTS (**Telescopic Transit Square**). These instruments are depicted in Figure 1. Second, while surveyors often use lasers, these are not so common with roller alignment crews. Third and perhaps most important, that is the equipment used by the web alignment crews may be more or much more accurate that those used by surveyors.

Figure 1 – Foundations of alignment tooling - Courtesy OASIS

While the origin of this equipment was surveying, it was greatly improved on by companies such as Brunson Instrument Co., Keuffel & Esser, Kern, Wild and Leica around WWII for a variety of aerospace, marine and industrial applications [2]. The improvement results in "first order" accuracy of one second of angle (0.001" over 17 feet, or 5 microns per meter, or 5 micro-radians). This is an order of magnitude or two better than mere surveyor's equipment that could be as sloppy as one minute of angle. This best practice accuracy was comfortably below the specifications of paper machine builders such as Beloit Corporation and Valmet (now Metso). Both companies quickly adopted the instruments and incorporated them into roller design and maintenance standards in the 1970's and other web machine builders from other industries followed. Recently some web plants have employed **gyroscopic** tooling and **lasers** as the centerpieces for precision roller alignment. A very complete review of roller alignment methods [3] and methodologies [4] are given by Roisum.

LITERATURE REVIEW OF ROLLER ALIGNMENT

There are about 70 articles from the Roisum Database [1] containing the keyword root 'align.' Of these, the great majority falls into three almost equal-sized and mutually exclusive categories. Let me call them purely practical, intermediate and purely theoretical just for simplicity, though I am sure this will draw criticism for over-simplified labeling. The 'purely practical' alignment articles are written primarily by practitioners of the craft of alignment and are published in both conference proceedings and magazines. For the sake of discussion, I will give this mostly craft based knowledge the collective shorthand of what we *could* do. In these articles you will find very practical discussions of the equipment used for alignment, usually optical tooling, as well as a bit about the process of alignment itself. The best of these practical articles are given in the bibliography [6-20].

The second category is articles written by web handling experts that straddle the 'practical-theoretical' range. They border on what we should do, but offer little detail on how to achieve it and little in the way of quantification. To be fair, limitations of the venue, typically magazine columns, preclude much detail of any kind. Also, web products and machinery are so diverse that 'one-size-fits-all' recommendations may not be appropriate. These practical-theoretical articles are by the authors Roisum [22-28] and Walker [29-41].

The third or 'theoretical' category primarily originates from research professors and students from the WHRC (Web Handling Research Center) as well as other authors who give papers at IWEB (International Web Handling Conference). These conference papers describe models and/or experimental verification of algorithms that *could* be used to determine maximum allowable misalignment. However, it is not the purview of research to take the step from theory to practice and thus what we should do with regard to roller alignment maintenance has not yet reached the people who actually do it. Some papers on seemingly unrelated topics, such as guiding and spreading, also could be co-opted to build alignment tolerance guidelines. The theoretical category is almost exclusively the province of only three authors: Professor J.K. Good of the WHRC (and his students and colleagues) [43-47], Dr. John Shelton [48] and Tim Walker [49-51].

IN-PLANE AND OUT-OF-PLANE MISALIGNMENT

One of the major shortcomings of roller alignment as currently practiced is that it treats in-plane, Figure 2, and out-of-plane, Figure 3, and level and square as equally important even when we know they are not [54]. There are two reasons for this over-simplification of using a level and square coordinate system instead of an in-plane and out-of-plane reference. The first reason is that using level and square is imminently practical as almost all of our alignment tools (tramming stick excepted) are based on this quite convenient reference frame. Imagine the practical challenge of having a roller-based coordinate system that changes with every roller in a machine. The second reason is not as sound. That is people who do roller alignment almost never have the web handling knowledge that the rest of us take for granted. Either we as a web community have not done our job in clearly communicating what we know or the alignment community has not paid attention or both.

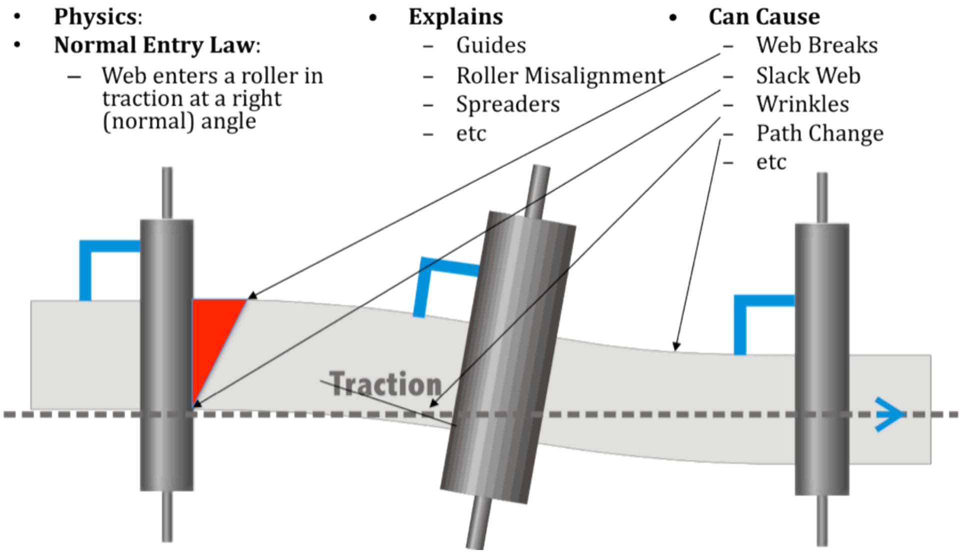


Figure 2 – The four risks of in-plane misalignment

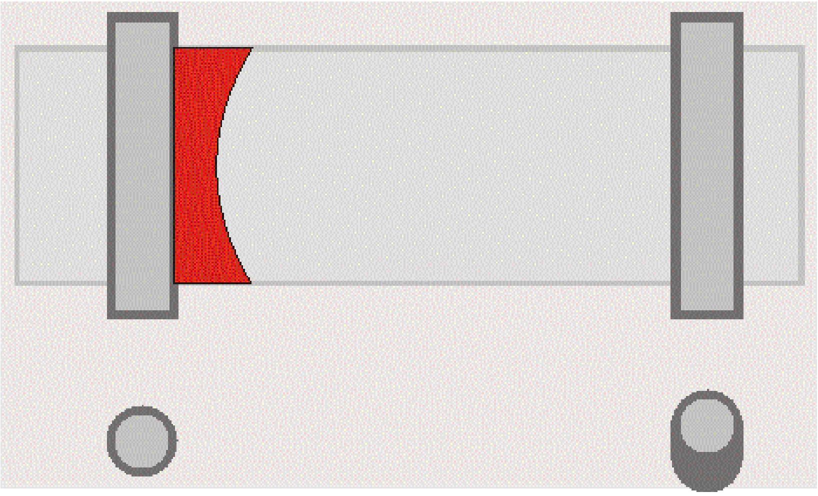


Figure 3 – Out-of-plane twisting

We know for a fact that in-plane misalignment is around 2 orders of magnitude fussier. Thus, we will focus on this direction for suggesting guidelines for alignment tolerances and will base these guidelines on wrinkling and web break models. However, as a practical concession, we will use the in-plane misalignment tolerance to suggest tolerances for level and square knowing that it will be good enough for most situations, even if it is more than needed for many. Even so, we will teach as best as we can that certain situations such as the accumulator, Figure 4, displacement guide and similar geometries do not require a 'full' alignment. In specific situations such as these, the cost of alignment can be reduced by more than half because one direction, squaring, requires little or no attention and that is by far the most expensive direction.

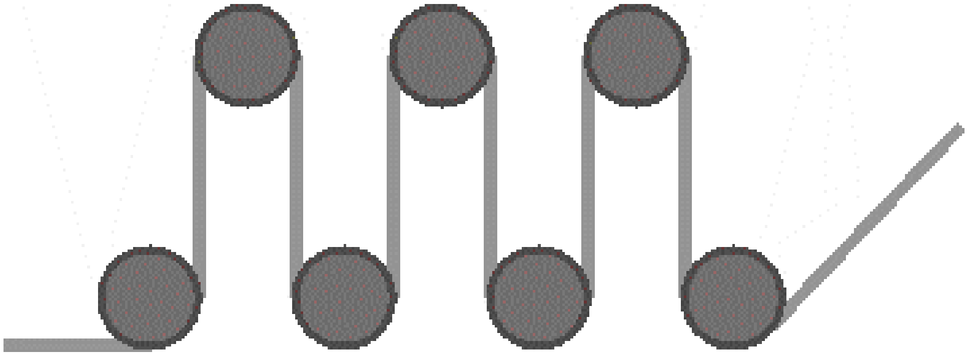


Figure 4 – The Accumulator does not need a ‘full’ alignment

INGOING AND OUTGOING SPECIFICATIONS

GETTING STARTED BY SIMPLIFYING

The first thing we must do is to reduce the number of numbers that an alignment crew must deal with. It is absolutely absurd, for example, to have crews run misalignment calculations for every relevant failure mode such as web breaks, slack edges, wrinkles, misregistration and so on. It is equally absurd for crews to check all web materials against a single model even though thickness and modulus and tension do affect allowable misalignment. It is also absurd for the alignment crew to calculate each span even though the L/W of the span ratio, wrap angle, COF and other factors will affect allowable misalignment. So, as much as researchers might dismay, the ideal number of numbers an alignment crew must deal with is just one (outgoing specifications) where an implicit second number (ingoing specifications) is merely a check to make sure that the instrumentation and technique (and roller condition) is good enough for the situation.

So, the simplification to one number means that we must take **worst case** and apply it to most cases. Any exceptions will be few, clear and listed as a case-by-case situation. So, what would this worst case be? Well, it clearly would be **in-plane misalignment** that will set the allowable upper limit also for out-of-plane, level and square even if those directions might be more tolerant. Exceptions here, such as the already mentioned accumulator, are dealt with succinctly and clearly. As an example, “internal rollers on vertical accumulators only need to be leveled unless there is compelling evidence of the need to square. The lead-in and lead-out rollers still need a full alignment”.

Another worst-case situation to consider will be a combined material and geometry. Here, parametric analysis given below will show that **thinner materials and stiffer modulii** are fussier. We would use the worst combination expected to be run on that machine. Geometry is not so fussy as the L/W's do not vary a lot in most cases (small slitter rewinders excepted. Still, we check short and narrow spans with a parametric study to see which is fussiest. Also, while it is true that slippery materials or rollers that are lightly wrapped may allow for some or even notable tolerance for misalignment, we should probably not count on it. Thus, worst case would be a coefficient of web-roller friction and wrap angle sufficient to give traction across the entire width.

Finally, we need to consider failure mode. Again, we will take worst case of simple, well-modeled failure modes such as the onset of a slack web as well as diagonal wrinkling. Here, we must make a few (conservative) assumptions to make the problem tractable. The **onset of a slack edge** *might* be a practical problem, i.e., waste and delay, because of moment transfer problems and because shifting the tension to the tight side that might yield or even break the web. Empirical paper web break models indicate that the break rate is proportional to (approximately) the square of tension [55]. Thus, a slack side means the other side must be twice as tight and thus could increase break rates in that span by 4X. Similarly, **diagonal wrinkling** would almost always be a problem if the wrinkle crossed the roller as a bulge. However, rather than relying on tension settings to open the window of acceptable operation (even though we would do that as a first practical step), we would conservatively set our criteria to **clear wrinkling at any tension**.

PARAMETRIC ANALYSIS FOR COMMON MATERIALS/MACHINES

As a lead-up to suggesting guidelines for allowable roller misalignment tolerances, we could exercise the wrinkling models in a parametric fashion. However, rather than simply varying the parameters by some arbitrary factor, such as 1/2X and 2X, we can constrain the analysis to what sets of parameters are *commonly* found. By common I mean those materials that are made in hundreds if not thousands of plants. These common materials would of course include paper and paper board that span the thickness range in the largest of the web industries. To really explore the web handling space we would have to include extremes of the film world including PE (polyethylene) and PET (polyester). Finally, we will also consider aluminum foil as an even more extreme of modulus from the metals world as a proxy for other less common foils such as copper or steel. What were not considered in this analysis were rubber, nonwovens, tissue and textiles. One reason is that the properties of these materials are extremely varied. Also, there is some reason to be cautious about using these existing models because they do not consider anisotropy, of which these materials exhibit in abundance, or ultra low shear strength. The program we use is the very convenient 'Wrinkle Predictor" AbbottApp [56-57] because it is most accessible but still uses the well published and tested wrinkling models [43-52]. The I/O screen of this app that will run on any computer or smart-phone running a modern browser is shown in Figure 5.

○Metric Units ●US Units ☐Text **Wrinkle Predictor** Help

Tension lb 20.0
Misalignment mil 9.61
Width in 20.04
Span in 30.02
Diameter in 12.03
Wrap ° 90
Frict.Coef. 1.00
Thickness mil 3.00
Modulus Mpsi ? 0.797

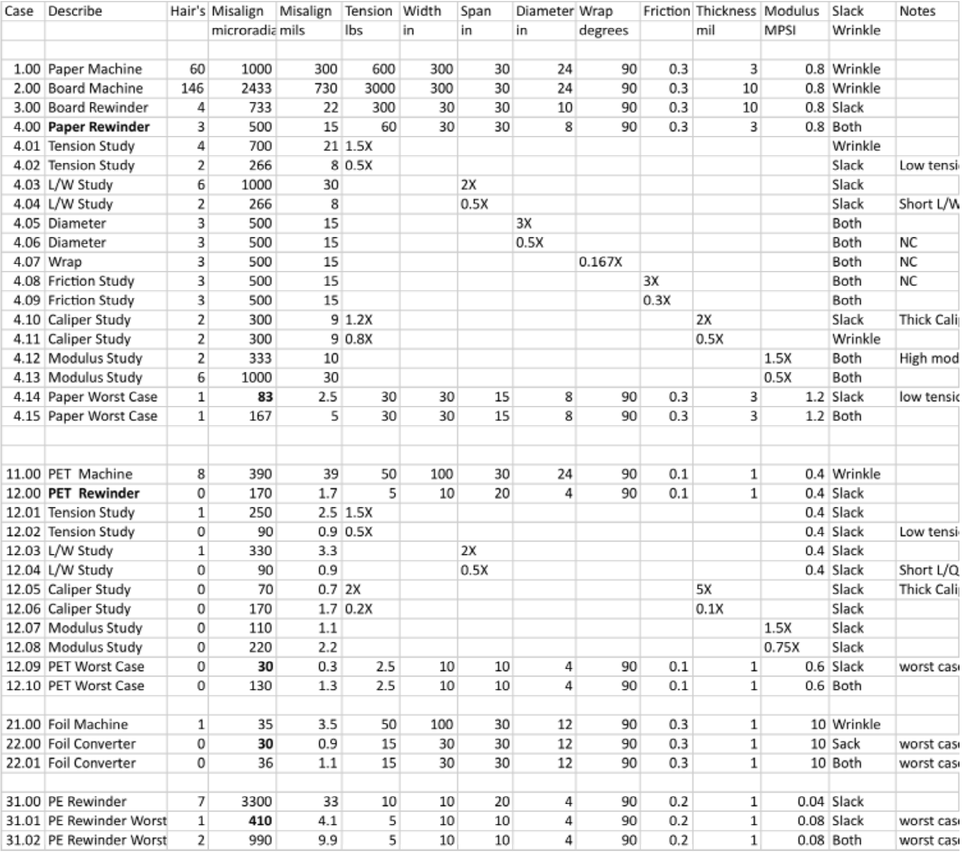
Slack Edge Yes
TD Offset mil 9.60
Hard Wrinkles 2.4°

© Copyright 2012 Abbott Apps Click for User's Manual

Figure 5 – I/O Screen snapshot of the Abbott Wrinkle Predictor App

We begin in the paper industry because it is the largest, oldest and best understood/researched. It is also one where precision alignment has been practiced far longer and is much more widespread and any other. Here we note that wider machines include board and paper machines and the production winders that follow, as well as offline equipment such as rereelers, offline supercalendars and offline coaters. We will also consider their customers that follow which have much narrower machines. Both paper and board will be considered as they nicely bound the extremes of thickness and absolute modulus. The values used for the base case analysis will be typical and will be varied in a range that captures most of what will be found in the paper industry.

We begin by comparing wide paper (Case 1.00) and board (Case 2.00) machines. Not surprisingly we find that **thinner materials, such as paper, require tighter tolerances**. In the case of paper we find that it is about 2 ½ times as fussy as board. Before we proceed we will make two observations. The first is that the misalignments required to throw a wrinkle across a roller, around ¼” and ¾” for paper and board respectively, are quite believable. There is an element called a guide roller that follows nearly every unwind on the couple of thousand paper machine production winders. This skewable roller can and has been adjusted over such a range and it will throw wrinkles at values very similar to what was predicted by wrinkling models. The second observation may be even more telling. That is **the tolerance to misalignment is nearly two orders of magnitude greater than specified and maintained by most paper machine builders as well as their paper mill customers**.



Case	Describe	Hair's	Misalign	Misalign	Tension	Width	Span	Diameter	Wrap	Friction	Thickness	Modulus	Slack	Notes
			microradia	mils	lbs	in	in	in	degrees		mil	MPSI	Wrinkle	
1.00	Paper Machine	60	1000	300	600	300	30	24	90	0.3	3	0.8	Wrinkle	
2.00	Board Machine	146	2433	730	3000	300	30	24	90	0.3	10	0.8	Wrinkle	
3.00	Board Rewinder	4	733	22	300	30	30	10	90	0.3	10	0.8	Slack	
4.00	**Paper Rewinder**	3	500	15	60	30	30	8	90	0.3	3	0.8	Both	
4.01	Tension Study	4	700	21	1.5X								Wrinkle	
4.02	Tension Study	2	266	8	0.5X								Slack	Low tensi
4.03	L/W Study	6	1000	30			2X						Slack	
4.04	L/W Study	2	266	8			0.5X						Slack	Short L/W
4.05	Diameter	3	500	15				3X					Both	
4.06	Diameter	3	500	15				0.5X					Both	NC
4.07	Wrap	3	500	15					0.167X				Both	NC
4.08	Friction Study	3	500	15						3X			Both	NC
4.09	Friction Study	3	500	15						0.3X			Both	
4.10	Caliper Study	2	300	9	1.2X						2X		Slack	Thick Cali
4.11	Caliper Study	2	300	9	0.8X						0.5X		Wrinkle	
4.12	Modulus Study	2	333	10								1.5X	Both	High mod
4.13	Modulus Study	6	1000	30								0.5X	Both	
4.14	Paper Worst Case	1	**83**	2.5	30	30	15	8	90	0.3	3	1.2	Slack	low tensic
4.15	Paper Worst Case	1	167	5	30	30	15	8	90	0.3	3	1.2	Both	
11.00	PET Machine	8	390	39	50	100	30	24	90	0.1	1	0.4	Wrinkle	
12.00	**PET Rewinder**	0	170	1.7	5	10	20	4	90	0.1	1	0.4	Slack	
12.01	Tension Study	1	250	2.5	1.5X							0.4	Slack	
12.02	Tension Study	0	90	0.9	0.5X							0.4	Slack	Low tensi
12.03	L/W Study	1	330	3.3			2X					0.4	Slack	
12.04	L/W Study	0	90	0.9			0.5X					0.4	Slack	Short L/Q
12.05	Caliper Study	0	70	0.7	2X						5X		Slack	Thick Cali
12.06	Caliper Study	0	170	1.7	0.2X						0.1X		Slack	
12.07	Modulus Study	0	110	1.1								1.5X	Slack	
12.08	Modulus Study	0	220	2.2								0.75X	Slack	
12.09	PET Worst Case	0	**30**	0.3	2.5	10	10	4	90	0.1	1	0.6	Slack	worst cas
12.10	PET Worst Case	0	130	1.3	2.5	10	10	4	90	0.1	1	0.6	Both	
21.00	Foil Machine	1	35	3.5	50	100	30	12	90	0.3	1	10	Wrinkle	
22.00	Foil Converter	0	**30**	0.9	15	30	30	12	90	0.3	1	10	Sack	worst cas
22.01	Foil Converter	0	36	1.1	15	30	30	12	90	0.3	1	10	Both	worst cas
31.00	PE Rewinder	7	3300	33	10	10	20	4	90	0.2	1	0.04	Slack	
31.01	PE Rewinder Worst	1	**410**	4.1	5	10	10	4	90	0.2	1	0.08	Slack	worst cas
31.02	PE Rewinder Worst	2	990	9.9	5	10	10	4	90	0.2	1	0.08	Both	worst cas

Table 1 – Roller Alignment: Parametric Analysis Summary

Next we take rewinders or converting machines that are considerably narrower than the paper machines that supplied the parent rolls. Here again we note that paper (Case 4.0) is a bit fussier than board (Case 3.0) on narrow machines. Since paper is fussier and more common than board we will investigate other parameters using this as the base case. Next we proceed to tension since it is readily available and is known to affect the propensity and severity of wrinkling. There is a 3:1 greater fussiness at low tension than high tension but the concerns are different. **At a low tension we have a slack edge** that may cause problems feeding through a nip or cause yielding or even breaks on the opposite side that is forced to carry more tension as a result. **At a high tension we have a wrinkle crossing a roller** that would be considered a rejectable defect for nearly all products. Span ratio (Cases 4.03 and 4.04) did have a notable affect on required alignment tolerance and not surprisingly we find that **short spans are fussier just as narrower machines are**. The next series of roller parameters that were varied were geometrical and were found to be uninteresting. Next we varied caliper/thickness, but did so in a reasonable way by presuming that the operator would select slightly heavier tensions for heavier materials, but not quite proportionally as simple theory would suggest. If this is done we find that thickness does not have a large effect. Finally, taking all the worst cases and combining them together we find that **the small paper**

converter is at the very edge of practical alignment measurement (80 micro-radians) and maintenance (2.5 mils or 600 microns), even without any safety factor.

Next we move into the film industry and look at PET as a good representative of modulus at the high end as well as thickness at both the low and high end. The results are very similar to what we see in paper as would not be surprising because PET, though having distinctly different chemistry, has material properties that are similar. What is different, however, is that converting machines that run PET can be a bit narrower and thus we expect greater absolute and relative alignment fussiness that is indeed born out by the parametric analysis. Another difference is that PET can be much thinner and thus we expect even more fussiness and again the parametric study shows this to be the case. In summary, **worst case PET is just *below* best commercial standards for design and maintenance of rollers**.

From this we might investigate foil that is stiffer still and can also be narrow and thin. We use aluminum foil though copper, steel and other metals are obviously also made as webs. Foils would thus be expected to be the 'canary in the coal mine' for web machine precisions and this study clearly bears this out. Also, real world experiences indicate that required alignment tolerances are below or well below what would be considered commercial best practices. While Tim Walker's foil study [41] indicates that the models may be overly conservative, it is pretty clear that we are only granted a bit of leeway. Thus, as may not be surprising, other techniques must be found to running challenging materials such as foil. These are summarized in Table 2.

1.	Fewest rollers possible
2.	Ultra low wrap angles
3.	Ultra low tensions
4.	Chevron grooving
5.	Alignment – ultra tight or
6.	Alignment – intentional in-plane misalignment on very light wrap angles

Table 2 – Web Handling 'Tricks' to Handle Foils

Finally, we can move to the other extreme of modulus which is PE (polyethylene) which is about 20X more flexible than paper. Not surprisingly, we see an expected greater tolerance to misalignment. While construction materials, nonwovens and textiles were not considered, for reasons given above, we can now appreciate why these industries were among the last to even consider precision alignment.

Now is a great time to step back and look at the bigger picture of the web industries. We see the biggest challenge is the very machines that are the least likely to use best practice alignment; the narrow web manufacturers and especially converters. We see that even without safety factors, they need to key roller alignments to around the thickness of a human hair. On the other hand, the paper industry that has nearly a half-century of precision alignment experience has over-done their specifications. In other words, almost every machine builder and machine user has got it wrong.

Of course, calculation is not for everyone. By this I don't just mean the modeling challenged. I also mean the many situations that are not well described by the models such as given in Table 3.

1.	Baggy and cambered webs
2.	Intentional profile (e.g., selvedge edges, cutouts, etc.)
3.	At spreaders
4.	Low shear modulus materials (nonwovens, textiles)
5.	High modulus materials (PET?, foils)
6.	

Table 3 – Some Alignment Model Shortcomings

Also a case can be made that empirical studies could be faster and/or more accurate than models. Thus, for all of these and many other situations it would be good to have an alternative method for determining the 'threshold of pain' for a specific material and machine. This is relatively quick and easy to do in many cases. The first this is to identify a worst-case situation for that process as guided by experience and/or the parametric analysis given above. This would include things like, for example, a combination of high modulus and short spans.

The second step is to set up a roller that can be easily moved in a direction nearly aligned with the inplane direction. This might be as simple as finding a bearing housing whose bolts can be loosened. The third step is to find a safe way to move the bearing housing while the machine is running in a precise fashion with a dial indicator. Finally, we move the roller and observe the onset of troughing and then a wrinkle crossing a roller as a bulge. This should be done in both directions to increase the accuracy of the test and to eliminate the need to find a precise zero. This experiment should be done at thread speed if the process allows for two practical reasons: wrinkling sensitivity is usually greater at thread speed and less material is wasted. This technique is just an adaptation of early experimental work to verify wrinkling models [43-52].

A QUESTION OF SAFETY FACTORS

There are many reasons that we need to apply a generous safety factor for the case of roller misalignment. First, distinctly different problems add and accumulate to the same end result. So is the case of brittle web breaks; excess tension can come from the sum of nominal web tension, tension variations from drive control errors, bagginess, stress concentrations (flaws in the material) in addition to mere misalignment. In the case of shear wrinkles; bagginess, roller diametral profile errors and other factors add to the problem and thus conspire to make wrinkles at misalignment angles less or far less than predicted for a perfect world.

A second reason for a conservative safety factor is that you don't want to just clear failure. This leaves no room for the roller moving on its own with time. Recall from the companion paper that foundations and framework move for a variety of reason. If you just clear the wrinkle today, you might move into wrinkling next season due to changes in soil moisture/temperature that pushes foundations around.

A third reason and most important reason for a conservative safety factor is reliability. These models and experimental verifications were based on immediate failure. We don't want do break/wrinkle within one second, one minute or maybe not even in one day (86,400 seconds). Reliability is why, for example, Beloit Corporation sized bearing life so conservatively; a L-10 of 50 years. It was not that the machines had a life of 50 years, some are in service even a century later. It is because we want reliability to be high enough in year one because there are thousands of bearings on the machine. While a stochastic design is much harder than a deterministic one, we are obliged to at least consider that the real world is more complicated and these complications often conspire to make troubles more frequently than if the world was simple; having but a single cause for any problem.

So what kind of well-studied safety factors can be found in our industry? I can think of three. The first is overstressing rotating elements, i.e., roller components such as journals. Here, Beloit Corporation had internal standards for all commonly used metallurgies. These safety factors varied from as little as 4 to as high as 8 depending on the metal alloy. So while the engineers accounted for all sources of bending and torsion to which calculated stress concentration factors would also be considered, the engineer could not know all things. Possible overloads by the customer and corrosion and other complications would reduce reliability/safety unacceptably unless a safety factor was applied. The second safety factor we might learn from is on web tension. Remarkably, most webs and machines run a tension that has a safety factor of 4-10 on ultimate strength. A much more detailed but specific study is a web break rate as the 2nd or 3rd power of tension [55]. With these three quite disparate but similarly sized safety factors we might be emboldened to apply something similar to critical misalignment angles for end slackness and diagonal shear wrinkles. We might go as little as 4 for slow non-demanding processes, such as might be found in some corners of converting, to as high as 10 for industries such as paper, glass and steel where there is no such thing as a little problem.

ALIGNMENT CLASSES

Lastly, we must also accommodate the many, many, situations where neither modeling nor experiment is practical or even possible. Just one of the many examples here is when designing a machine for a product and process that has never been run. To that end we can be guided by a methodology that worked reasonably well for defining acceptable roller deflections. That is to use the concept of quality classes. Table 4 shows just such a proposal.

Class	Value microradian	Application
A	< 20	Alignment tooling, brittle webs such as ceramic coated
B	20	Metals, paper
C	100	Converting general
D	1000	Rubber, textiles
F	> 1000	A web handling fail, but adequate for ribbon, rope or string

Table 4 – Proposal Alignment Quality Classes

This table is not entirely spun out of whole cloth. Rather, the classes are already what is considered best practice in some industries. In particular, dry end paper ingoing alignment tolerances have long been specified in the B class of 20 micro-inch range by several of the largest builders and are nearly universally practiced by maintenance. Of course, the instrumentation to do so must and is better than that. Class C is what a few roller suppliers and few machine builders and a few consultants already specify for converting.

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