

**Identification of Failure Mechanisms in  
Correcting Roll Bearings of a Continuous Galvanizing Line**

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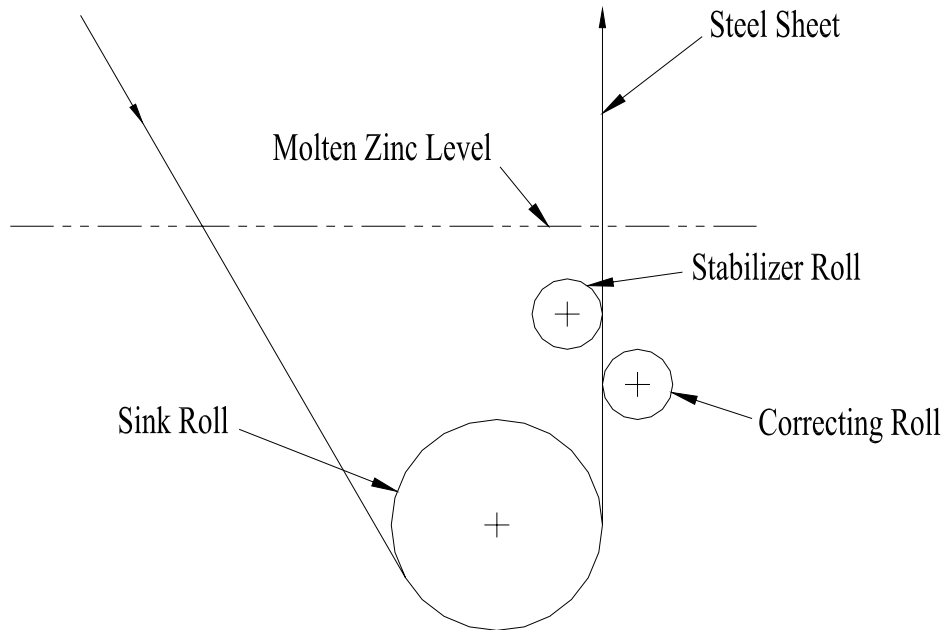
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## **Identification of Failure Mechanisms in Correcting Roll Bearings of a Continuous Galvanizing Line**

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### **Abstract:**

Failure due to lock-up of the bearings on the correcting rolls in a continuous galvanizing line can be a costly and redundant problem. Through the use of a mathematical model the load vectors on the correcting roll bearings were established to observe potential causes of bearing lock-up. As a result of the identified loading characteristics, utilization of hollow rolls and/or reduced clearance bearings may provide potential reduction in occurrences of bearing lock-up.



**Figure 1: Diagram of a typical continuous galvanizing zinc pot hardware.**

### **Introduction:**

To maximize performance life for many applications, steel must be made corrosion resistant by galvanizing with a zinc (or zinc alloy) coating. In order to apply a metallurgically bonded zinc coating to a steel substrate, the steel must be “hot-dipped” into a pot of molten zinc. However, for long, flat steel sheet products, which are to be used in high volume automotive and construction applications, the steel substrate must be galvanized on a continuous basis in order to minimize economic constraints.

Continuous galvanizing is performed by threading the steel strip through a series of three rolls submerged in a pot of molten zinc [Figure 1]. The large bottom roll (“sink” roll) allows the strip to change direction and return upward out of the pot. The two smaller rolls sit in succession above the sink roll and help stabilize the strip as it is exiting the zinc bath, minimizing zinc overcoating and maximizing quality.

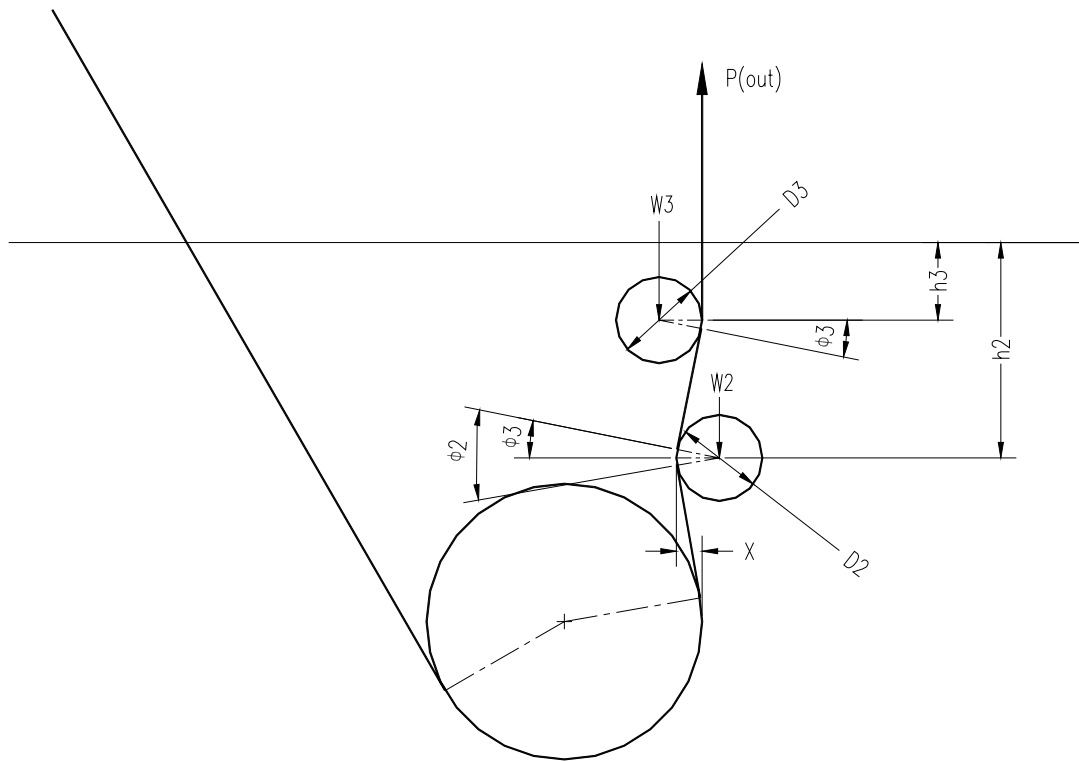
The correcting roll is independent of the other two rolls and is movable in the forward and back direction parallel to the zinc surface (i.e. from right to left in Figure 1). This adjustable correcting roll may be used to control the stability of the strip within the array of submerged rolls. As a result, repositioning of this roll can alter the loading of the support bearings on these submerged rolls, especially the correcting roll bearings.

Variable loading of the pot rolls is significant in that it may have a detrimental effect on the performance and wear of the support bearings. Currently, as a result of extreme loading conditions and metallurgical attack by the liquid zinc, these support bearings can have a rather abbreviated, finite life (typically between 6 and 30 days). Failure of these bearings dictates production shutdown and pot roll rig change out at a significant cost.

Similarly, limited bearing materials and designs result in retarding friction that can be quite high, even to the point of roll stoppage. Bearing lock-up is regularly prevalent in the correcting roll when very thin-gage strip (less than 0.014") is being galvanized. With the thin cross-section of the steel strip a high tension cannot be exerted on the strip (which would assist in roll rotation) because the yield strength of the hot strip (at 460°C) could be easily exceeded.

As a result, a need exists to review these galvanizing roll lock-up issues as they relate to the galvanizing line geometry and operating parameters, as well as bearing orientation and materials.

**Theory:**



**Figure 2: Identification of geometrical variables for a typical galvanizing line roll rig assembly**

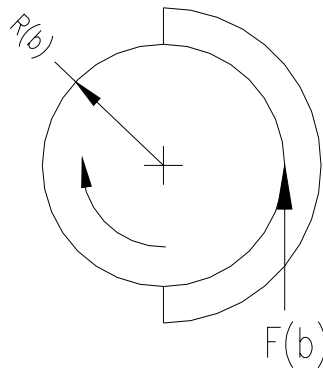
Several projects have been undertaken [Refs. 1 – 6] to compare the wear life of commercially available galvanizing pot hardware bearing materials. For the most part these investigations have concentrated on ranking the material wear and corrosion

characteristics and not necessarily reviewing the physical failure mechanisms of the bearings from a design standpoint.

In order to understand the failure mechanisms of a roll/bearing system, a theoretical understanding of ideal operating conditions must be evaluated. For simplicity, a continuous galvanizing line can be modeled as a flat belt and pulley system [Refs. 7 – 10]. However, instead of possessing a “driving” pulley and a corresponding “driven” pulley, a galvanizing pot roll rig assembly merely contains three “driven pulleys” (i.e. rolls) as the steel sheet is being pulled from the bath by downstream power transmission equipment.

The output tension on the sheet exiting the bath is generally controlled tightly, but the bearing loads and sheet tensions between the rolls are impossible to directly measure and difficult to calculate.

### Bearing Frictional Force



**Figure 3: Typical journal bearing assembly for galvanizing line rolls**

The bearing friction was calculated using the following basic equation.

$$F_B = \mu_B * N \quad (1)$$

Where  $\mu_B$  is the friction coefficient between the bearing and the sleeve (varies with material selection) and  $N$  is the resultant normal force.

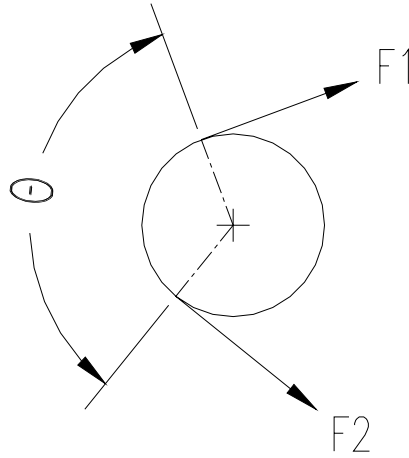
The retarding torque caused by the bearing friction was calculated from the following equation.

$$T_B = \mu_B * N * R_B \quad (2)$$

where  $R_B$  is the radius of the rotating bearing sleeve.

The low viscosity of liquid zinc, combined with the high loads and low rotational speed of the rolls, does not allow a hydrodynamic film to form. [Ref. 11] Thus, metal-to-metal contact exists and equations for a lubricated bearing design can be neglected.

### Calculation of sheet tensions throughout the galvanizing rolls



**Figure 4: Contact angle of the sheet on the roll**

Shigley and Mischke [Ref. 8] define the following equations for the general condition of a flat belt (i.e. a steel sheet) moving over a rotating drum. Rotation of the roll is made possible exclusively by the transference of horsepower from the sheet to the roll via the friction between the sheet and the roll.

The general equation for the relationship between input and output tensions of a belt moving over a rotating drum is:

$$[(F_1 - F_c) / (F_2 - F_c)] = \exp(\mu_s * \theta) \quad (3)$$

where  $F_1 > F_2$ ,  $\mu_s$  is the friction coefficient between the sheet and the roll surface and  $\theta$  is the wrap angle of the sheet on the roll.

Note: The term  $\exp(\mu_s * \theta)$  is often abbreviated as “m”.

The centrifugal force of the moving steel sheet,  $F_c$  was calculated by the following equation.

$$F_c = q * v^2 \quad (4)$$

where  $q$  is the mass of the belt per unit length and  $v$  is the belt velocity (ft/sec)

Now, if the torque ratio of the incoming and outgoing sheet is utilized and the retarding torque from the bearing is included, the following equation is obtained:

$$\{(F_1 - F_c) * R_r / [(F_2 - F_c) * R_r + T_B]\} = \exp(\mu_s * \theta) = m \quad (5)$$

where  $R_r$  is the radius of the roll body

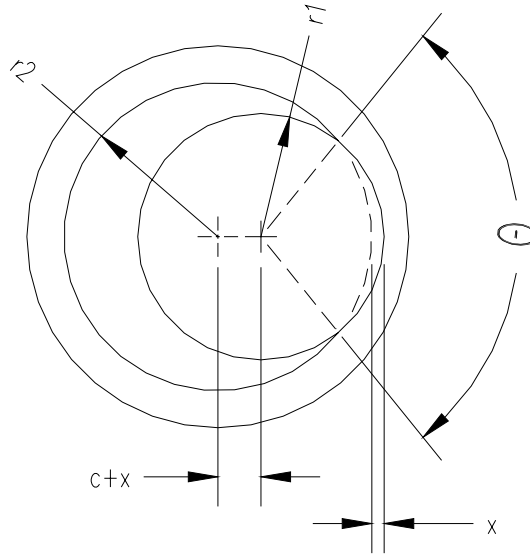
Rearranging:

$$(F_1 - F_c) * R_r / m = (F_2 - F_c) * R_r + (\mu_B * N * R_B) \quad (6)$$

With this equation the sheet tensions between each of the rolls may be calculated. Then, with these sheet tensions, the resultant normal force vectors on the stabilizer and correcting rolls can be calculated. Utilizing computer algorithms of these equations, the input conditions can be easily varied and alternate reactions observed.

### Calculation of Bearing “wear-in”:

Due to the harsh operating conditions and the limited corrosion resistance of currently available bearing materials, high radial clearances (up to 0.25”) are used in the journal bearings of continuous galvanizing rolls. Therefore, the rotating journal bearing sleeve will quickly wear itself a “groove” into the stationary bushing piece in the direction of the normal load on the bearing. The angle of this wear groove will be a function of the bearing dimensions, radial clearance (c) and wear-in distance (x). [see Figure 5] The wear-in rate varies for different bearing material systems.



**Figure 5: Diagram of bearing “wear-in”**

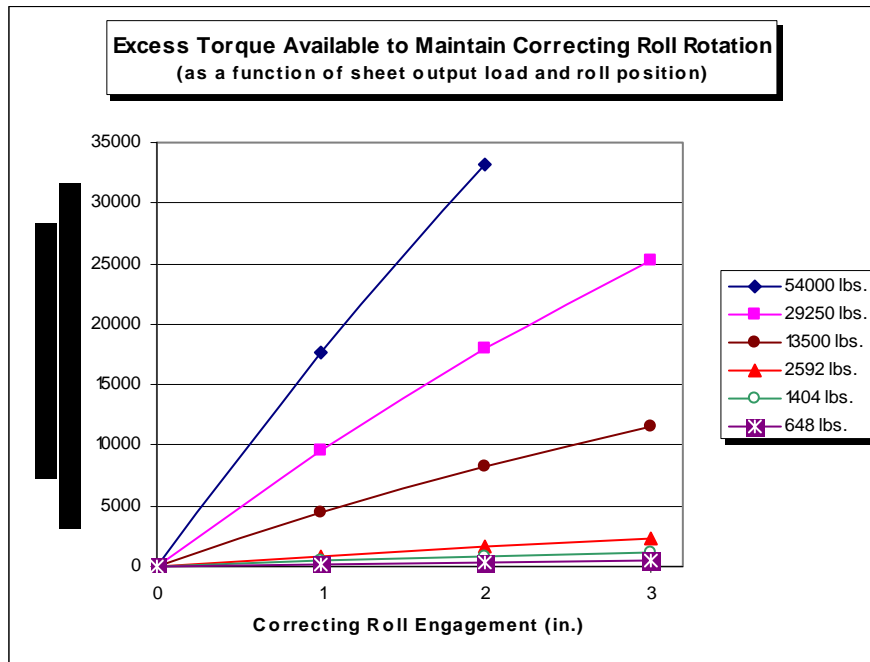
Based on the above, the general equation for wear-in angle is:

$$\theta = 2(180^\circ - [\cos^{-1} \{[(r_2)^2 - (r_1)^2 - (c+x)^2] / [-2(r_1)(c+x)]\}]) \quad (7)$$

**Analysis:****Table 1: Outline of typical galvanizing line geometry and variables**

Strip Speed:	600 fpm	= 10 ft/s
Strip width:	60 in.	
Strip gage:	0.014 in.	
Strip mass per unit length (slug/ft):		0.0877
Sheet Output Tension:	3250 psi	= 2730 lbs.
Correcting Roll Engagement:	3 in.	
<b>Sink Roll:</b>		
Roll Diameter:	D = 32 in.	r = 16 in.
Roll Face Length:	74 in.	
Bushing I.D.:	D = 5.5 in.	r = 2.75 in.
Bearing Sleeve O.D.:	D = 5 in.	r = 2.5 in.
Radial Clearance:		0.25in.
Bearing Length:	4 in.	
Bearing Friction Coefficient	0.3	
Centerline Depth in pot:	44 in.	
Roll Weight [in air] & [in zinc]:	5500 lbs.	1286.3 lbs.
Strip-to-Roll Friction Coeff.	0.6	
<b>Correcting Roll:</b>		
Roll Diameter:	D = 10 in.	r = 5 in.
Roll Face Length:	74 in.	
Bushing I.D.:	D = 3.13 in.	r = 1.56 in.
Bearing Sleeve O.D.:	D = 3 in.	r = 1.5 in.
Radial Clearance:		0.0625 in.
Bearing Length:	2.5 in.	
Bearing Friction Coefficient	0.3	
Centerline Depth in pot:	25 in.	
Roll Weight [in air] & [in zinc]:	1600 lbs.	374.2 lbs.
Strip-to-Roll Friction Coeff.	0.6	
<b>Stabilizer Roll:</b>		
Roll Diameter:	D = 10 in.	r = 5 in.
Roll Face Length:	74 in.	
Bushing I.D.:	D = 3.13 in.	r = 1.56 in.
Bearing Sleeve O.D.:	D = 3 in.	r = 1.5 in.
Radial Clearance:		0.0625 in.
Bearing Length:	2.5 in.	
Bearing Friction Coefficient	0.3	
Centerline Depth in pot:	9 in.	
Roll Weight [in air] & [in zinc]:	1600 lbs.	374.2 lbs.
Strip-to-Roll Friction Coeff.	0.6	
<b>Snout:</b>		
Incoming Sheet Angle (from bath surf.):	60 degs.	1.047 rads.

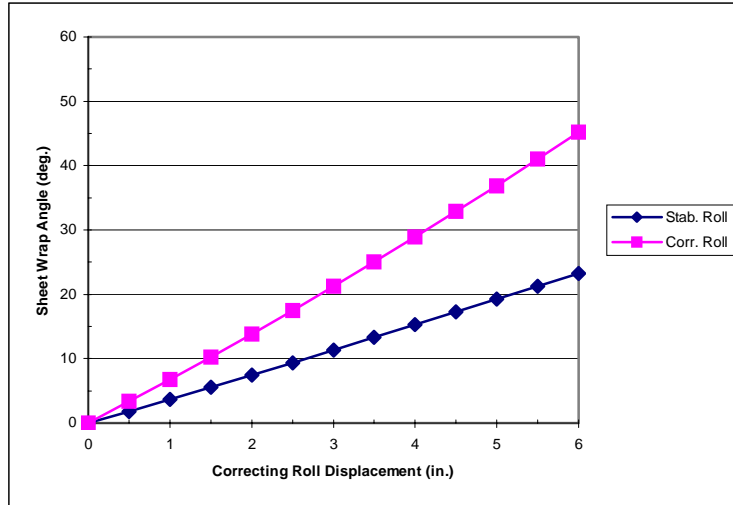
Table 1 outlines the standard variables that were used for the subsequent analyses in this study. Variables that were changed for various iterations were noted respectively.



**Figure 6: Comparison of torque caused by the sheet on the roll and the retarding torque caused by bearing friction for various sheet output tensions and engagement distances**

(Note: Correcting roll engagement relates to the lateral distance that the outer diameter surface of the correcting roll has been moved beyond the passline of the sheet.)

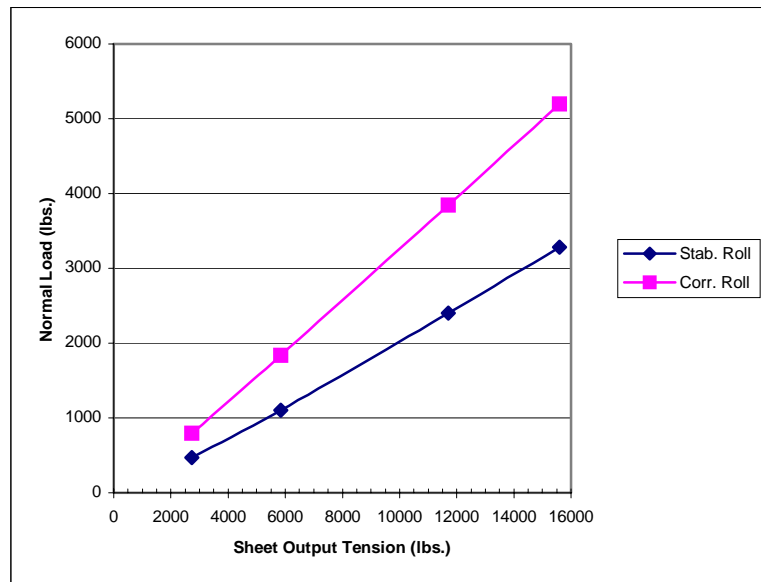
Since the correcting and stabilizer rolls in a galvanizing line are not driven by any mechanical means other than the frictional torque between the steel sheet and the roll, it is important that this rotational torque exceed the resistance torque produced in the journal bearings. Figure 6 provides a visualization of the torque available to maintain correcting roll rotation under various operating conditions. From the data in this chart it can be seen that the rotational torque from the sheet exceeds the retarding torque created in the bearings for every scenario presented. However, at very low sheet tensions (e.g. as a result of reduced sheet gage and width), the excess torque becomes only marginal.



**Figure 7: Effect of Correcting Roll Impingement on Sheet Wrap Angle on Rolls.**

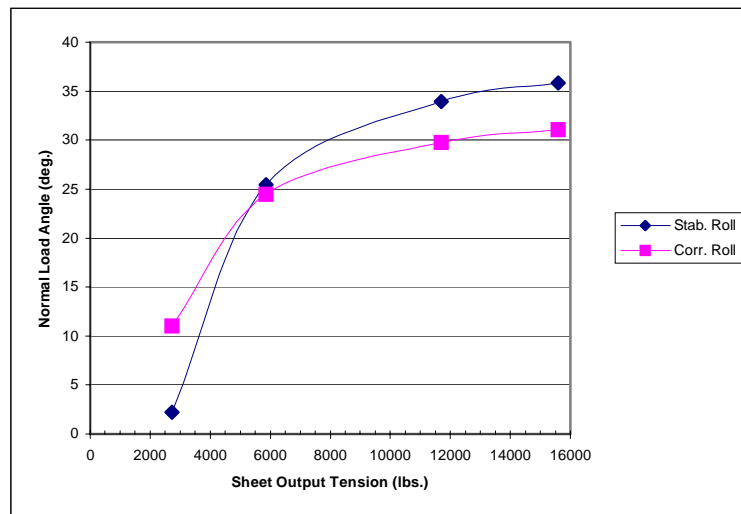
At the same time, the amount of rotational torque that can be transferred from the sheet to the roll is proportional to the wrap angle of the sheet onto the roll. Figure 7 indicates the amount of wrap angle present for the stabilizer and correcting rolls at various correcting roll engagement distances. It should be noted that many galvanizing lines only have a limited amount of maximum correcting roll engagement (typically, about 3 inches) and therefore a minimal amount of sheet wrap angle available to transfer rotational torque from the sheet to the roll.

Due to the vast differences (size, load, etc.) between the sink roll and the other two rolls, review of the sink roll was, for the most part, omitted from this investigation.



**Figure 8: Effect of Output Sheet Tension on Resultant Normal Load on Bearings.**

As noted previously, the magnitude of bearing friction is linearly proportional to the normal load in the bearings as a result of the sheet tension acting on the roll. As seen in Figure 8, the normal load on the stabilizer and correcting rolls increases proportionally to the line tension for a given roll engagement distance. Also, it can be observed that the normal load is much smaller than either of the sheet tensions engaging the specific roll.



**Figure 9: Effect of Output Sheet Tension on Resultant Normal Load Angle on Bearing**

Since the normal load in the bearings is a vector, it has both a magnitude and a direction. As Figure 9 clearly indicates, the amount of sheet tension pulled has an important effect on the normal load angle. This effect is minor in the range of 6000 lbs. to 16,000 lbs., varying little throughout this range. However, between 2000 lbs. and 6000 lbs. pulled tension, the normal angle changes drastically with slight changes in line tension. (Note: The normal angle is measured from horizontal.)

### **Discussion:**

Using the force and moment analysis, a mathematical model was generated to assist with the calculation of loads within the submerged roll system in a continuous galvanizing line. Utilizing this model, it was observed that the loading conditions on the rolls and specifically the journal bearings supporting those rolls are affected by geometrical configurations, materials of construction, product parameters of the steel being coated, the operating conditions of the line as well as other issues.

By calculating the resultant bearing loads at increasing levels of sheet force exiting the roll system, it becomes obvious that as the output load is increased the resultant normal load (and thus bearing retarding friction) continues to increase proportionally.

Interestingly, the mathematical model indicates that when operating within the allowable loading parameters of the yield strength of the steel sheet, the output torque on the sheet is sufficient enough to overcome the retarding torque from the bearings. Thus, theoretically the roll system should continue to rotate unabated without stopping or stalling.

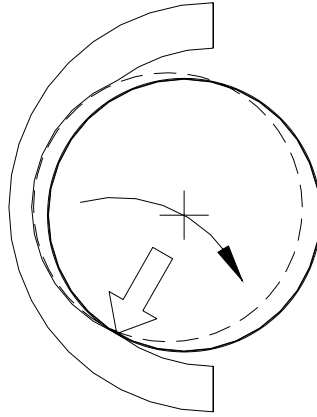
However, a condition exists in actual steel sheet galvanizing production where a “lock-up” of the journal bearings occurs on the stabilizer and correcting rolls whenever a product transition is made from a higher gage steel (>0.040” thickness) to a low gage steel (<0.014” thickness). For example, the galvanizing operation can run effectively at steady-state while a 0.060” steel is being galvanized, but once the product mix is switched to a 0.014” steel significant difficulty is experienced trying to keep the stabilizer and correcting rolls rotating.

This “lock-up” condition is counterintuitive to the results of the mathematical model [Figure 6 & Table 2], which shows that a decrease in line tension also decreases the bearing loading which reduces the retarding torque in the bearings.

**Table 2: Stabilizer and Correcting Roll Loads - Comparison between 0.06” and 0.014” Thick Sheet (10”dia. Rolls on 3”dia. Bearings)**

	0.06" x 60" wide	0.014" x 60" wide
Strip gage (in):	0.06	0.014
Strip width (in):	60	60
Sheet Output Tension (psi):	3250	3250
(lbs.):	11700	2730
Sheet Speed (ft/min):	600	600
Stabilizer Roll Normal Load:		
magnitude (lbs.):	2404.5	467.6
direction (degs. from horiz.):	33.91	2.19
Correcting Roll Normal Load:		
magnitude (lbs.):	3848.13	798.2
direction (degs. from horiz.):	29.78	11.00

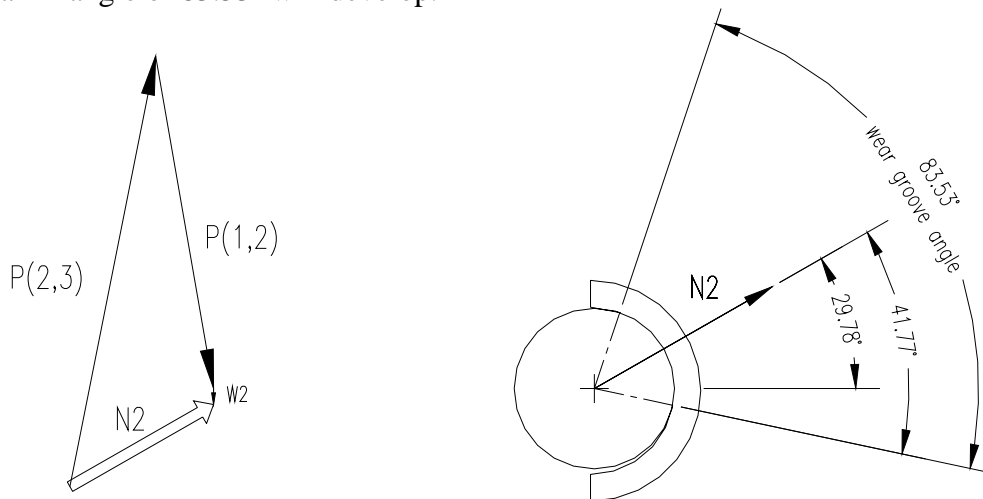
Thus, it is being hypothesized that the bearing lock-up condition is not necessarily due to excessive friction in the typical condition of the journal bearings. Rather, the lock-up is caused by instabilities during an apparent “fall-out” mechanism. “Fall-out” can be described as the journal bearings revolving out of the cradle groove that has been worn into the stationary bushing. [See Figure 10]



**Figure 10: Schematic Representation of Bearing “Fall-out” as a Result of Reduced Sheet Tension**

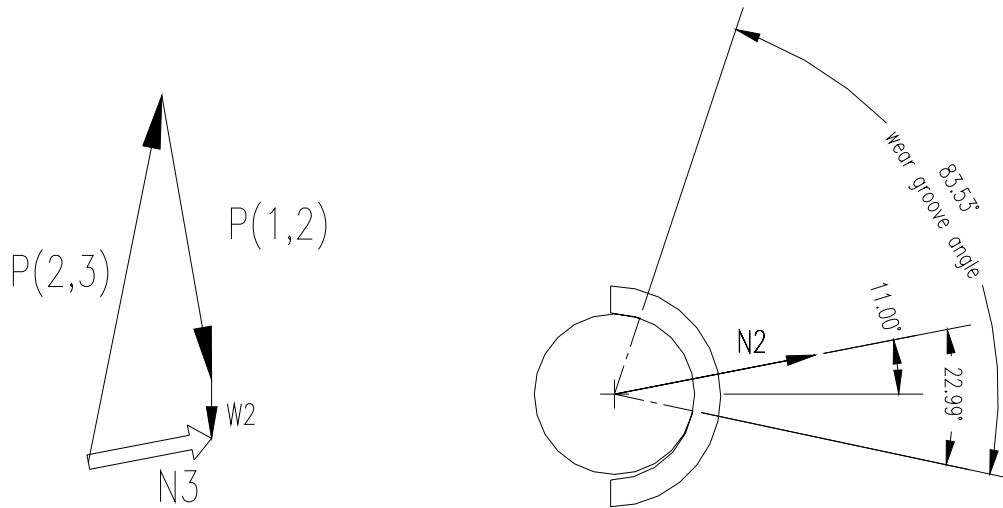
In order to better understand this hypothetical phenomenon, first consider the steady-state condition of a 0.060” thick steel sheet traversing through the submerged galvanizing rolls. (Note: Standard operating conditions of 60” wide sheet pulled at 3250 psi tension moving at 600 feet per minute sheet speed on 10” diameter rolls at a constant geometrical orientation will be maintained throughout this review.) Using calculations from the mathematical model [see Table 2], the force vector diagrams of these loads can be constructed for a correcting roll bearing to give a visual representation of the tension configurations. [see Figure 11]

Assume that an initial lateral wear-in distance of 0.02” will develop in the stationary piece of the correcting roll bearings at the angle of the normal vector. Thus, with a standard initial radial bearing clearance of 0.063” on a 3.00” diameter journal sleeve, a wear-in angle of  $83.53^\circ$  will develop.



**Figure 11: Resultant Normal Load Direction and Wear-in Angle for the Correcting Roll Operating Under 0.060” x 60” wide Steel Sheet at 3250psi Tension**

Now, if the sheet gage is transitioned to 0.014" thickness (as mentioned previously), then the normal vector angle drops significantly from  $29.78^\circ$  to  $11.00^\circ$ . (Note: Regardless of schematic scaling, the weight of the roll ( $W_2$ ) is identical for both Figure 11 and Figure 12.) As displayed in Figure 12, the new normal vector (at 0.014" gage) for the correcting roll is much closer to the direction of the corner of the previous wear-in angle. (Similarly, results for the stabilizer roll show an even more detrimental situation.) In the event that the normal angle would vacillate below the lower wear groove corner angle, a tremendously high stress riser with corresponding high friction load condition would develop, which could potentially lead to a lock-up situation.



**Figure 12: New Resultant Normal Load Direction for the Correcting Roll After Transitioning to 0.014" x 60" wide Steel Sheet at 3250psi Tension**

Although it is not difficult to predict that the magnitude of the resultant normal load would change dramatically at a reduced loading condition, it is interesting to discover the dramatic difference in applied angle of that resultant normal load vector. It is theorized that this angle of normal load is one of the defining factors in predicting whether bearing lock-up due to the "fall-out" mechanism will occur.

Also, to exacerbate the situation further, due to the vast dynamics of an industrial galvanizing line, a true steady-state condition is not feasible. The sheet tension is constantly fluctuating due to vibrations in the equipment, thermal expansion in the steel sheet [Refs. 12, 13], and numerous other factors. Thus, even if the aforementioned theoretical calculations indicate that the new normal vector angle is still within the seat of the original wear-in groove, variability in process parameters can create instabilities when the normal vector angle even approaches the wear groove corner.

Furthermore, basic engineering dynamics theory identifies that static friction is much more difficult to overcome than dynamic friction. Thus, once a lock-up situation occurs and the bearings stop, it may become impossible to reestablish rotation of the roll, even if higher loads induced by a higher sheet gage are reintroduced.

**Results:**

Calculations identifying possible mechanisms for bearing lock-up indicate that changes must be implemented either to the operating practices of the line or to the design and geometry of the system in order to reduce the potential for this lock-up.

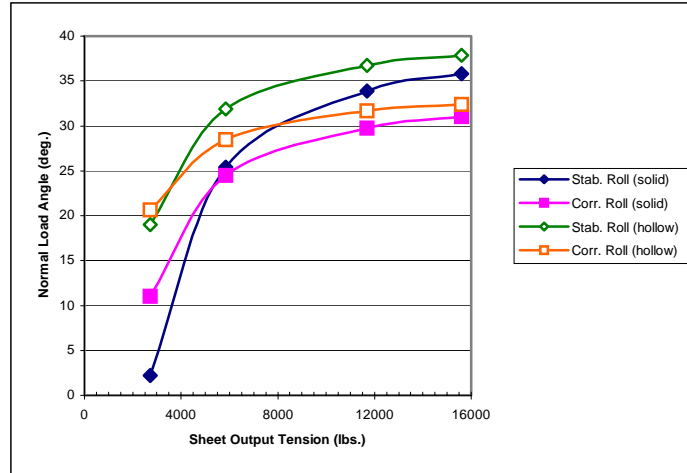
A first obvious solution would be to increase the magnitude and direction of the normal vector whenever a reduced load situation is encountered. This, however, is not an easy change to implement. Increasing the line tension is not necessarily feasible due to the low yield strength of the carbon steel sheet at 460°C and enhancing the normal vector angle by increasing the transverse impingement of the correcting roll is generally constricted by line hardware design.

On the other hand, changing the vertical load vector of the weight of the roll (i.e.  $W_2$ ) in molten zinc can significantly alter the angle of the normal vector. This can be implemented by utilizing hollow, centrifugally cast rolls versus solid metal rolls, which can provide up to a 60% weight reduction. (Many galvanizing lines already employ hollow rolls in standard practice.)

Another means of lowering the weight of a roll could be to reduce the outside diameter of the roll barrel. This change in O.D. can have a double benefit of not only reducing the weight, but also increasing the wrap angle of the sheet, which would allow more rotational torque to be transmitted from the sheet to the roll, potentially overcoming a higher level of friction. On the other hand, caution must be made when greatly altering roll diameter in that other considerations such as flexibility and shape of the steel sheet as well as strength characteristics of the roll assembly must be evaluated prior to a design change.

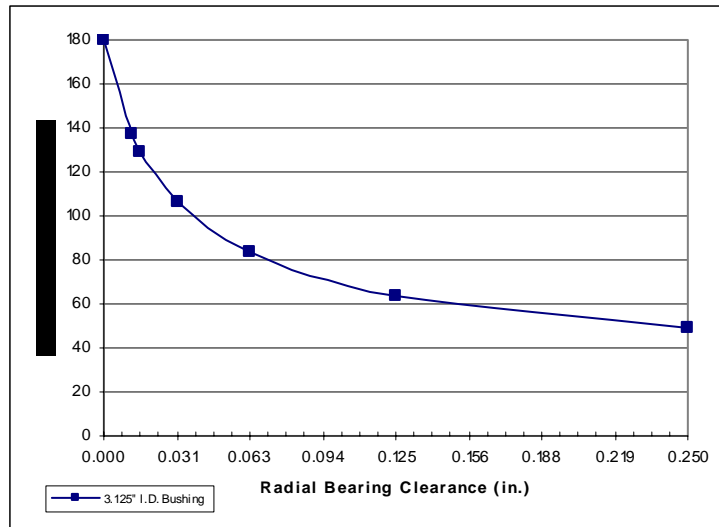
However, since the weight of the roll in zinc is relatively small compared with the loads induced by the steel sheet, the enclosed mathematical model calculates a minimal change in the magnitude of the resultant normal load from a change to lighter weight (i.e. hollow) rolls.

Conversely, Figure 13 indicates that reducing the roll weight not only beneficially provides a greater normal load angle compared with an equivalent solid roll, but more importantly the transition from a high load condition to a low load condition has less of an effect on a lighter weight roll. Thus, as described earlier, if the normal angle remains more constant when transitioning from a higher gage sheet (0.060") to a lower one (0.014"), then the probability of bearing "fall-out" and potential lock-up is theoretically reduced.



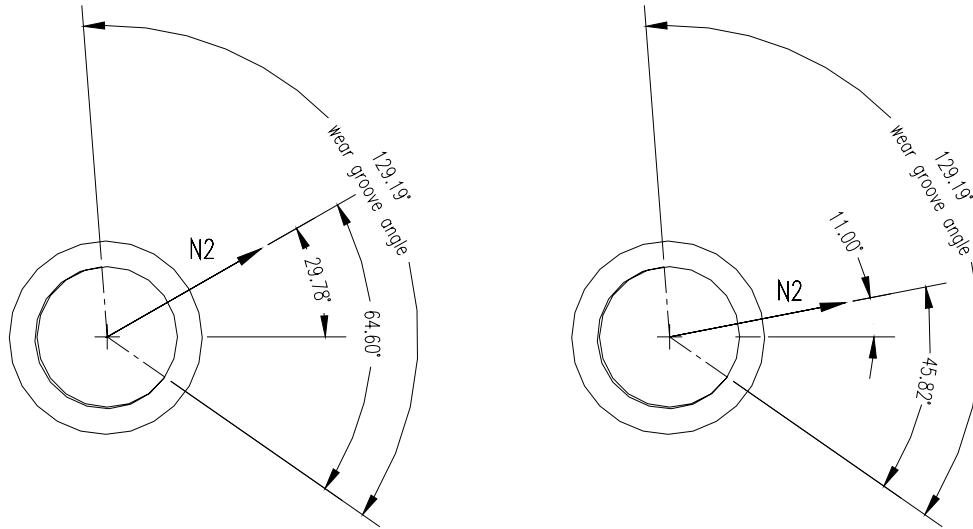
**Figure 13: Comparison of Normal Load Angle for Solid and Hollow Rolls**

If roll weight reduction does not cure the problem of lock-up (or if it is not feasible to implement), an alternative solution to minimizing bearing lock-up would be to reduce radial bearing clearance. A reduction in the radial clearance between the journal bearing sleeve and the static bushing can induce a greater wear-in angle for an equivalent lateral wear-in depth. [see Figure 14]



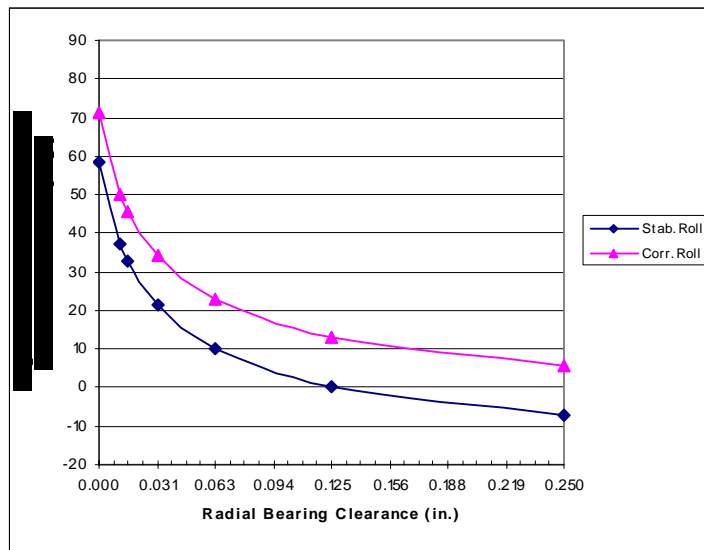
**Figure 14: Wear Groove Angle as a Function of Radial Bearing Clearance for an Original Dimension 3.125" I.D. Bushing after 0.02" Lateral Wear-in Depth**

If the radial clearance of the previously described bearings [Figure 5] is reduced from 0.063" to 0.016" then the wear groove angle (0.02" wear-in depth) changes from 83.53° [as noted previously in Figs. 11 & 12] to 129.19° [Figure 15] and the normal load vector is now closer to the center of the groove and less likely to "fall-out" due to system instabilities.



**Figure 15: Wear Groove Angle for 0.016” Radial Bearing Clearance in Conjunction with Normal Load Direction for the Correcting Roll Operating Under 0.060” x 60”wide (left) and 0.014” x 60”wide (right) Steel Sheet at 3250psi Tension**

And finally, Figure 16 describes how modifying the radial bearing clearance (for a 3.125” original I.D. bushing) affects the angle between the new normal load at 0.014” sheet thickness and the wear groove corner created at 0.060” thick sheet. It can be observed that this available “fall-out” angle for the stabilizer roll is less than zero for radial clearances greater than 0.125”. Thus, theoretically, the “fall-out” mechanism will most likely occur in the stabilizer roll after transitioning from 0.060” sheet thickness to 0.014” sheet and the probability for roll lock-up is significantly increased.



**Figure 16: Remaining Angle between the New Normal Load at 0.014” Sheet Gage and the Wear Groove Corner Created While Operating Under 0.060” Sheet Gage (for an original dimension 3.125” I.D. bushing after 0.02” lateral wear-in depth)**

**Conclusions:**

- A mathematical model was created to calculate the loading conditions within a galvanizing roll rig assembly operating in molten zinc at 460°C
- The mathematical model indicated that insufficient retarding torque exists in the bearings to cause lock-up of the stabilizer and/or correcting rolls during normal operation.
- The model is inconsistent with actual field performance where frequent bearing lock-up occurs when galvanizing light gage (<0.014" thk.) steel sheet.
- The light gage lock-up may be due to a bearing "fall-out" mechanism whereby the rotating journal sleeve becomes unseated from the worn bushing groove when a reduced loading situation is encountered.
- Two straightforward solutions exist to attempt to minimize bearing "fall-out":
  - 1) Reduce the weight of the rolls when submerged in the molten zinc bath.
  - 2) Minimize the radial clearance within the bearings.
- By reducing the roll weight (via a hollow roll), the normal load vector would maintain a more positive inclination even under lower load conditions.
- Minimizing the radial bearing clearance (from 0.063" to 0.016") would create a wider wear groove angle seat that would prevent bearing "fall-out" due to product load changes or system instabilities.

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