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Performance of Submerged Hardware in Continuous Galvanizing

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For over a decade, research and development on submerged hardware in continuous galvanizing pots has been carried out at Teck's Product Technology Centre. The outcome of numerous laboratory tests and field trials has demonstrated that dissimilar materials with comparable surface hardness are most suitable for the manufacture of roll bearings. Wear debris can be easily retained in bearings made of the same material, thereby negatively affecting bearing performance and service life. Bearings made of the same materials are also vulnerable to catastrophic failures. The dissolution of iron from the coated strip creates an iron-rich zone associated with a high concentration gradient in the vicinity of the sink roll. Consequently, the sink roll becomes a preferential site for dross pick-up. In operations involving extremely high temperatures, such as in Galvalume production, the material selection for pot hardware is immaterial to the final corrosion product of the hardware and the pick-up on the hardware.

Keywords *: galvanizing, coating, corrosion, GL, dross*

1. Introduction

A systematic study of the performance of roll bearings in continuous galvanizing baths was initiated in the International Lead Zinc Research Organization (ILZRO) Galvanized Autobody Partnership (GAP) program in the early 1990s. The construction and the commissioning of the test rig at Teck's (then Cominco Limited) Product Technology Centre took over four years and the first test did not start until 1999.[1)] Following over one decade of dedicated research and development work, Teck's understanding of the working environment of submerged hardware and the factors which affect the hardware's performance have been significantly improved. A concerted effort by hardware vendors, galvanizers, and the R&D community has resulted in a better choice of bearing materials and design which, in turn, has resulted in a significant improvement in bearing performance and service life. In the early 1990s, the average bearing life, hence the duration of galvanizing production campaigns, was only two to three weeks.[2)] Bearing life is no longer the limiting factor of the length of a production campaign for many galvanizing lines, and bearings are frequently used for more than one production run with minimal maintenance.

After witnessing the significant advances in bearing performance and service life, the attention of GAP program has recently been shifted to the problem of dross growth on roll surfaces in galvanizing. Dross pick-up on the rolls diminishes product quality, leading to significant loss of production time. To better understand the problem, a number of plant trials were carried out in the program, which have successfully unveiled the root cause of dross growth on roll surfaces. It is clearly demonstrated that the roll growth is mainly caused by the attachment of floating dross particles in galvanizing baths to the roll surface; and the corrosive deterioration of the roll surfaces serves as the precursor of the attachment. These trials have also revealed that in operations involving high bath temperature, such as in Galvalume (GL) production where the bath is over 600 ℃, the material selection for pot hardware is immaterial to the final corrosion product of the pot hardware and the pick-up on the hardware. Experiences of galvanizers indicated that advanced ceramics remain non-wet to molten Galvalume alloy for a couple of production campaigns only.

2. Main findings

In the following sections, the main findings in funda-

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mental analyses of the stress and strain state to which the bearing is subjected, and the results of laboratory tests and on-line trials will be summarized, and future R&D areas will be suggested.

2.1 Mechanics - stress and strain state

Our understanding of sink roll bearing performance has been largely limited to the performance of bearing materials and their interactions with the coating alloy. Although knowledge of the strain distribution in an operating bearing is of paramount importance, the analysis of the stress and strain state in bearings has been rudimentary until recently when a Finite Element Analysis (FEA) of the stress and strain distribution in a bearing during service was completed.[3)]

FEA analyses revealed that the effective stress in a sink roll bearing under normal operating conditions is quite small, far below the yield strength of the materials of which the bearing is made. It was also found that the radial clearance of a bearing has a strong effect on the magnitude of stress developed in the sleeve. For an industrial bearing subjected to a load of 19.6 kN, the maximum effective stress developed in the bushing was 18.9 MPa when the radial clearance was 1 mm, and 56.5 MPa when the clearance increased to 10 mm. These stress levels should be compared to Stellite No. 6 Alloy with a yield stress of 620 MPa at a temperature of 460 ℃. In other words, when the surfaces of the bushing and sleeve are smooth, therefore in full contact, the effective stress developed in a bearing is one order of magnitude lower than the yield stress of Stellite No. 6 Alloy. Understandably, advanced industrial materials designed for bearing applications, such as SiAlON, zirconia, WC coatings and proprietary iron- and cobalt-based superalloys, all possess a comparable, if not higher, strength at high temperatures. Accordingly, only elastic deformation takes place in all types of sink roll bearings under normal circumstances. However, sink roll bearings were frequently cast or prepared through the powder metallurgical route. Hence, their surfaces are rough and unpolished and, as a result, the matching surfaces of the bearing are not in full contact. Even if the surfaces of the bearing components are smooth at the beginning of their service life, the surface quality deteriorates due to the interaction of the bearing material with the molten galvanizing alloy. If one assumes that only 10% of the overlapping surfaces are in real contact, then the effective stress developed in the bearing is about 650 MPa, slightly higher than the yield strength of Stellite No. 6 Alloy at 450 ℃.

The plastic zone developed in the bearing sleeve is depicted in Fig. 1a. The plastic strain is quite small ($1.7x10^{-6}$)

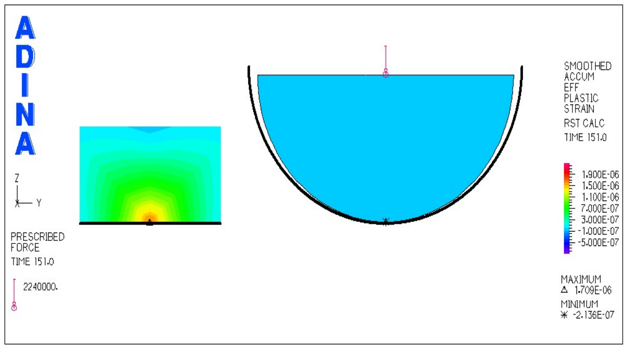


Fig. 1a. Accumulated plastic strain in the sleeve and shaft of an industry bearing with a radial clearance of 10 mm.

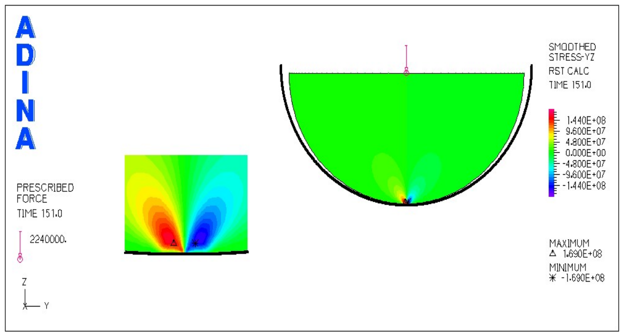


Fig. 1b. Shear stress σ_{yz} in the sleeve and shaft of an industry bearing with a radial clearance of 10 mm.

and localized in distribution. The shear stresses σ_{yz} are evenly distributed along directions making 45º with the loading axis, as shown in Fig. 1b. The value of the shear stress is only 169 MPa, relatively low in comparison to other stress components. When the bearing rotated, the highly stressed region in the sleeve experienced a cyclical loading and unloading condition. In other words, the sleeve experienced a fatigue process. Damage will accumulate in the sleeve surface layer, and cracks will eventually nucleate. Pre-existing surface defects, such as machining marks and corrosion-weakened phase boundaries or grain boundaries, could also act as crack nuclei, thereby bypassing the crack nucleation stage. The cracks, pre-existing or newly formed, would propagate under the cyclic loading condition. When these cracks intersect, detachment of the bearing material occurs. This type of damage is referred to as fatigue wear.

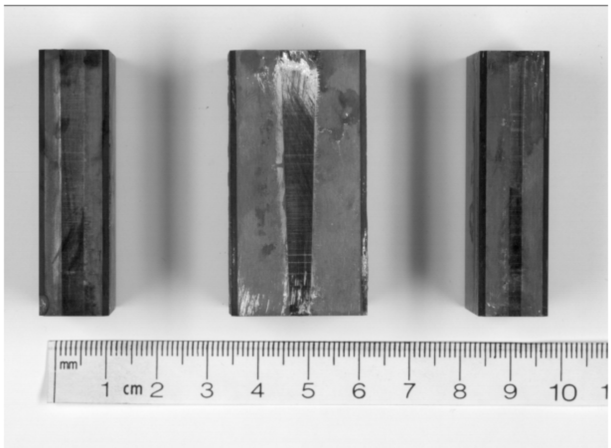
2.2 Bearing failure mechanisms

The present authors are not aware of any failures of sink roll bearings which were caused by the accumulation of long cycle fatigue damage. This is understandable for the following reasons.

(1) Industrial pot bearings are always over-designed

while their operating stress is well below the yield strength of bearing materials at the production temperature. Furthermore, most bearing materials contain wear-resistant hard particulates, such as carbides in cobalt-based superalloys and cermet coatings and TCP (topographic - closely packed) intermetallic compounds in proprietary iron- or cobalt-based superalloys. The protruding particles on the surfaces are capable of inflicting the surface of their counterpart component with abrasive damage in operation. Due to the fact that the magnitude of the stress is low and the plastic strain insignificant, this abrasive wear will manifest itself mainly as a grinding/polishing action. This action leads to an improvement of the surface smoothness and a corresponding increase in the effective bearing contact area. Consequently, the bearing stress and strain will become increasingly small, and the wear rate of a bearing is expected to diminish and gradually stabilize at a negligible level. The operating stress in the bearing is well below the fatigue limit of the material under such a circumstance, and the fatigue life of such a component is expected to exceed many million cycles. In production, the sink roll rotates at a rate of about 100 rpm. Consequently, if the fatigue wear dominates the service life of the bearings, then they should last at least months instead of weeks. With the development of SiAlON bushings and matching sleeves, the service life of sink roll bearings is reported to have extended to a few production runs with minimal maintenance required between the runs. However, the wear mode of these bearings is reported not to be fatigue wear, but to be the thinning down of the ceramic bushing if it is coupled with a stainless steel sleeve laser-clad with WC coating. The SiAlON is reported to be worn off at a rate twice that of the WC coating.

(2) Frequently encountered failure modes of sink roll bearings are abrupt cracking of bearing components when both components are made of the same superalloy which is hard and wear-resistant, however, brittle in nature; and the development of severe abrasive wear in bearings when both components, the bushing and the sleeve, are made of the same Stellite alloy. The latter type of failure mode is characterized by the formation of deep grooves with a size of up to 1 cm on the bearing surfaces. The identification of the culprit of such a wear mode took dedicated work by the researchers. It was widely believed in the galvanizing industry that the entrapment of dross particles in the bearing was the main cause of the development of this type of failure mode. However, industrial experience, as well as laboratory tests, indicated that such wear occurs in galvanneal campaigns as well in which the bath aluminum level is low and the dross particles forming in such a bath are δ phase or/and Τ phase. These particles possess low melting points and are much softer than the Stellite alloys at the galvanizing temperature of ~460 ℃. These particles are incapable of inflicting damage on the Stellite alloys in galvanizing. There are no structural features in the alloy which are of the same dimension as the grooves. Hence, this type of severe abrasive wear must be caused by factors other than the entrapment of dross particles in the bearing, between the bushing and the sleeve. A number of experiments were designed and carried out at Teck to unravel the true cause.[4)] These studies have established that the extremely high affinity of cobalt in the superalloys towards aluminum contained in the bath metal triggers the damage accumulation process. It was found that CoAl particles nucleated and grew on the bearing surface immediately after the bearings were submerged



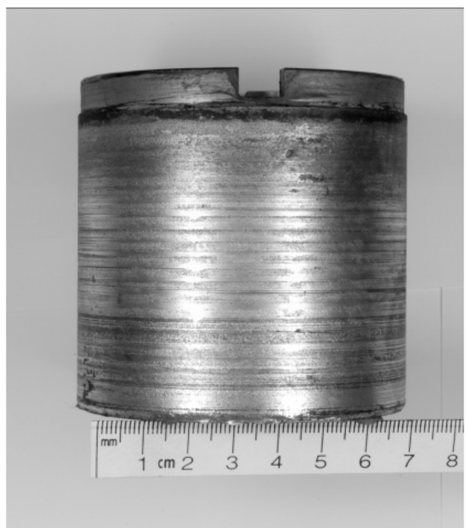


Fig. 2. The surface smoothness of the SiAlON blocks and the WC-coated 316L SS sleeve has been noticeably improved following a laboratory test, owing to the grinding/polishing effect induced by the sliding contact in the test.

into the galvanizing bath. These particles, although small initially, are much harder than the superalloy. Cutting into the bearing surface, these particles remove bearing material in the form of tiny but long chips with lengths several times their width. The wear debris quickly reacts with aluminum in the melt, and partly converts to CoAl fibre. This wear debris deposited mainly onto the bushing surface. The abrasive wear process accelerates with the generation and deposition of wear debris of an ever increasing size. Consequently, the dimensions of the wear grooves increase with the service time until the severe damage triggers instability in bearing operation. The service life of all Stellite bearings is frequently limited to two weeks due to the development of severe abrasive wear.

In recent years, more and more galvanizers use sink roll bearings made of dissimilar materials. Frequently, the sleeve of the bearing is made of stainless steel laser-clad with WC-based cermet or superalloy possessing a relatively high toughness, such as Stellite Alloy #6. The stainless steel substrate affords a high toughness, and the WC coating provides hardness comparable to that of its counterpart at elevated galvanizing temperatures. Recent tests carried out at PTC revealed that SiAlON bushings are compatible with sleeves made of a variety of existing superalloys or coatings designed for sink roll bearing applications, including 316L SS laser-clad with WC coating, Stellite Alloy #6, Alloy T800 (a cobalt-based superalloy), MSA2020 (an iron-based superalloy), etc. In these tests, the bearings were subjected to minor abrasive wear only. The surface smoothness of the SiAlON bushings frequently was largely unchanged after the test. On the other hand, the surface roughness of the sleeves invariably increased following the test. Examinations of the cross-sections of the sleeves following tests in a GL bath clearly revealed the root cause of increased surface roughness. It was mainly because the matrix of the superalloys was progressively corroded under the aggressive attack of the molten Zn-Al alloy at the elevated temperature. Although the strengthening carbides or topographically closely packed (TCP) intermetallic particles in the alloys were largely un-corroded, the corrosion-deteriorated surrounding matrix weakened its support of these particles. These particles were cracked and removed from the matrix. One sample of a WC coating laser-clad to the 316L SS sleeve is shown in Fig. 3. The binder of the coating is an iron-based superalloy. It can be seen that the binder was preferentially corroded, and its support of WC particles was significantly weakened. The spherical WC particle retained a flat top, indicating that it was in direct contact with the surface of the SiAlON and ground against it in the test. However, a transversal crack developed through the carbide slightly ahead of the corrosion front. It is expected that the top part of the carbide will chip off from the coating soon. Fragments of carbides were detected in the retained GL alloy on the sleeve. Based on the above observation, one can conclude that the fragmentation and chipping off of strengthening particles in the superalloys or coating following the corrosion-induced deterioration of the matrix or binder is one failure mechanism at work. Such a mechanism was probably also at work in the test in the GI bath, although the corrosion of the matrix of the superalloy or the binder of the coating would occur at a much lower rate. Another noticeable feature is that the wear of the sleeves was much less than that of the SiAlON in tests in the GI bath. Such an observation has been confirmed by data collected in field service of bearings consisting of SiAlON bushing and WC-coated 316L SS sleeve in galvanizing production. It was reported that the wear rate of the SiAlON bushing is at least a factor of two higher than that of the WC coating. These observations suggest that either the hardness of the WC coating can be further adjusted or another type of carbide, slightly less hard than WC, can be employed to reduce the wear to the bushing because it is much more expensive than the sleeve.

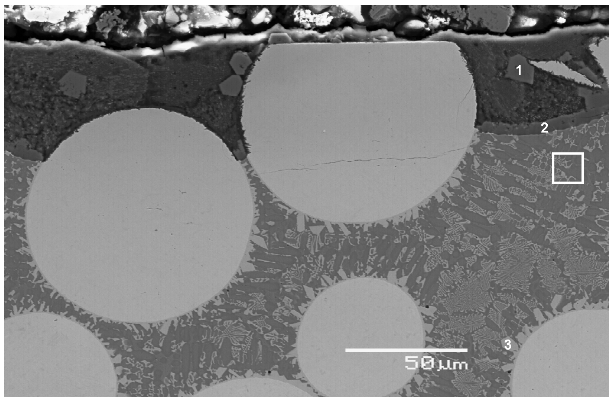


Fig. 3. Cross-section of a WC-coated 316L SS sleeve after being tested against a SiAlON bushing in a GL bath. The binder of the coating corroded severely, and its support of the WC particles was weakened. A transverse crack developed within the carbide slightly ahead of the advancing corrosion front in the coating. The particle (1) and the intermetallic layer forming at the corrosion front (2) are both of the τ_5 composition.

3. Dross buildup on rolls

3.1 Experimental description

Degradation of roll surfaces in continuous galvanizing leads to poor product quality. The degradation manifests itself in the form of buildup of dross particles on the roll surface. In fact, dross buildup on sink rolls is one of the main causes of line stoppages in galvanizing production. This problem is much more severe in GL production, and line stoppage in GL production is mostly caused by relentless roll pickup.

A survey carried out earlier in the GAP program of ZCO-15 indicated that sink rolls are almost always made of ASTM CF3M, a cast form of 316L SS. As a result, R&D work in the program has been focused on dross buildup on 316L SS. To improve our understanding of the effect of operating conditions on the buildup in an effort to minimize it, and to identify new materials which better resist the attack of molten galvanizing alloys, two types of tests have been carried out concurrently in industrial galvanizing lines in the last few years.[5),6)] In one type of test, dubbed the dynamic test, samples made of 316L SS were welded to both sides of the sink roll and also to various sites on the supporting roll arms. The samples were harvested after one production campaign. In another type of test, referred to as the static test, rod samples made of 316L SS were suspended on a specially designed rack and dipped in the bath. These samples were withdrawn individually at predetermined time intervals. The bath chemistry was monitored using Teck's aluminum sensor system for the duration of the tests. One test was carried out in a GI production campaign, another in a GA production campaign, and a couple of tests were carried out in GL baths.

3.2 Observations

Results obtained from these tests can be summarized as follows:

(1) 316L SS corrodes in molten Zn-Al alloys and the corrosion mode varies with the aluminum level of the alloys. Chromium and nickel are mostly bleached out from the stainless substrate during the corrosion process. An inhibition layer based on Fe_2Al_5 could form on the steel surface if the bath aluminum level is high enough; otherwise the corrosion product is based on the δ phase. However, the threshold level of aluminum for the formation of the inhibition layer could not be accurately established. Frequently, an inhibition layer forms only when the bath aluminum level is higher than ~0.17%.

(2) The corrosion of the roll surface serves as a precursor to the roll buildup. Top dross particles (Fe_2Al_5) suspending in the molten coating alloy is isomorphous with the inhibition compound forming on the roll surface. As a result, these particles can easily attach to the corroded surface. The main growth mode of the roll pickup is the agglomeration of the added on particles.

(3) Judging by the fact that the severity of dross growth on samples attached to various locations of a sink roll and its supporting arms increases with an increasing proximity to the sink roll surface, an iron content gradient must exist in the vicinity of the sink roll. This notion is consistent with the understanding that iron dissolution from the incoming strip is the main source of iron in the galvanizing pot. Iron-rich melt on the surface of the coated strip is being squeezed out when the strip comes into contact with the sink roll surface, resulting in the iron-rich zone at the vicinity of the sink-roll.

(4) Consequently, management of temperatures, particularly, the strip entry temperature, can significantly affect roll growth in galvanizing. Maintaining a low strip entry temperature and a low bath temperature can reduce iron dissolution, thereby reducing roll pickup; maintaining a strip temperature slightly higher than the bath temperature can discourage the nucleation of dross particles in the vicinity of the sink roll, thereby reducing the roll pickup rate.

(5) Continuous galvanizing lines are known to employ uncoated sink rolls in production without any penalty if the bath aluminum level is maintained at ~0.20% and higher. This is because the roll surface is protected by a thin inhibition compound and the coating bath is relatively clean because the iron dissolution rate is low at such an aluminum level.

(6) Tests carried out in GL baths indicated that the growth on test materials, including some cobalt-based superalloys, is invariably the quaternary extension of the Fe-Al-Si ternary compound of τ_5 which is the bottom dross in GL production.

(7) Industrial experience suggests that totally preventing dross growth on the sink roll is still impossible. No coating has survived the severity of the environment in GL production, and no material, advanced ceramics included, can stay long non-wet by the GL coating alloy.

Current research interest lies in the role of sink roll groove geometry as related to dross buildup on the roll surface. Computer modeling work is planned to investigate whether the melt flow characteristics play a role in the nucleation and growth of dross in these grooves.

Acknowledgements

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References

1. L. Battiston, Project Report No. 6, GAP Program ZCO-15, Teck Metals Ltd., Mississauga, Ontario, Canada (1999).

2. S. George, Pot Hardware Durability, Proc., Galvanised Steel Sheet Forum - Automotive, 15-16 May 2000, London, UK, p. 153 (2000).
3. N.-Y. Tang and K. Zhang, Operating Stress and Wear of Sink-Roll Bearings, Proc., Galvatech '07, Osaka, Japan (2007).
4. K. Zhang and N.-Y. Tang, Reactions of Co-Based and Fe-based Superalloys with a Molten Zn-Alloy, *Mater. Sci. Tech.*, **20**, 739 (2004).
5. K. Zhang, N.-Y. Tang, F.E. Goodwin and S. Sexton, *J. Mater. Sci.*, **42**, 9736 (2007).
6. D. Liu, Project Reports, No. 2 and 3, GAP Project ZCO-15-4, Teck Metals Ltd., Mississauga, Ontario, Canada (2007).