The Galvanized Autobody Partnership

2020-2022

Program and Research Plans

August 2019

International Zinc Association
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USA
www.zinc.org
## Plan Overview and Summary of Proposed Budget

<table>
<thead>
<tr>
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<th>Title</th>
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<tr>
<td>ZCO-53</td>
<td>Hot Dip Galvanizing of Third Generation (3G) Advanced Steels</td>
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<td>ZCO-70</td>
<td>Hot Press Forming Process and Product Variables Effects on User Properties</td>
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<td>ZCO-82</td>
<td>Improving Zinc Coating Adhesion</td>
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Galvanized Autobody Partnership

Overview of Proposed 2020-2022 Program

I. EXECUTIVE SUMMARY

This catalog contains the twelve programs that are proposed for the 2020-2022 Galvanized Autobody Partnership (GAP). It is evolved from the seven successful Galvanized Autobody Partnership programs operated in 3-year sequences between 1999 and 2019 that were sponsored by a large number of steel and automotive companies and their suppliers. Over this period, more than $27 million was committed in cash by sponsors and also by additional grants and in-kind funding from governments and other bodies. The details of these contributions are shown in the Table I.

Table I. GAP Program Funding History

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Additional sources of funding continue to be sought from governments, allied industry associations and other sources globally. Cash sponsorships in the GAP program have always allowed other funding commitments to be attracted to the GAP program, allowing further expansion of activities.

The continuing objective of the Galvanized Autobody Partnership is to retain and grow the market for galvanized sheet and autobody structures via technical innovation. Overall, this is met by focusing on continuing improvement of galvanized steel products and their processing to
meet ongoing challenges faced in the automotive market. This includes ensuring the hot dip galvanizability of new steel grades that are being introduced to meet the objectives of automakers, together with the processing and performance issues related to these steels. Reflecting this objective, the activities of the 2020-2022 Galvanized Autobody Partnership Program are divided into three Focus Areas:

- Galvanizing high-strength steels for lightweight automobiles
- Improving quality of hot dip coatings
- Performance of galvanized automotive steels

Research programs are organized to meet the objectives in each of the three Focus Areas.

As in the past GAP programs, the steel industry, auto industry and their suppliers can sponsor 2020-2022 GAP programs in two ways. The first is to fund Focus Areas of four programs each at the cost of $9,200 each. Sponsorship of the full GAP program can therefore be accomplished by funding the three Focus Areas for a total of $27,600. This admits a company as a sponsor into each of the programs in each focus area. Alternatively, you may sponsor individual GAP programs from among the different focus areas at a cost of $4,600 each.

The continued consolidation of the steel industry and loss of many separate operating units into merged steel producers, led to requirements several years ago for minimum funding based on hot dip galvanizing capacity. This has continued into the 2020-2022 program. For companies with less than 2 million MT of annual hot dip galvanizing capacity, minimum annual sponsorship of $13,800 has been set. This is equivalent to purchase of one $9,200 Focus Area plus one additional $4,600 project. For companies between $2 million and $5 million MT of total annual hot dip galvanizing capacity, a minimum sponsorship of $23,000 has been set. This is equivalent to purchase of two Focus Areas and one additional single project. Companies greater than $5 million MT capacity are asked to contribute supplemental sponsorship beyond the $27,600 for the three Focus Areas because such companies include many former operating units that were formerly GAP sponsors in their own right. Discussion of an appropriate level of sponsorship with IZA is encouraged. It is recognized that many companies, both small and large, have contributed to the GAP program by purchasing all three Focus Areas in the past and therefore the above figures are set as minimum guidelines to ensure reasonable participation in today’s reconfigured steel industry. Funding beyond these minimums are strongly encouraged if the GAP program is to have sufficient funding for the planned programs in 2020-2022. As noted before, the cash contributions to the GAP program are expected to be leveraged, allowing a much larger program to be achieved.

For zinc producer members of the IZA Technology and Market Development Committee, the funding is now included in the IZA core funding structure.

Since 1999, a total of 67 steel, zinc and other companies have sponsored in excess of $27 million in galvanized automotive steel research through the Galvanized Autobody Partnership. The
GAP program, by integrating programs on this topic, has provided significant benefits to sponsors versus funding of isolated programs, as done prior to 1999. A list of sponsors of the 2017-2019 GAP Program is shown in Table II. We expect that most, if not all these sponsors, will re-commit to the GAP program for its 2020-2022 term and will be joined by other companies as new sponsors, allowing the new GAP program to meet its goals. Membership in the GAP program is open to any company that would have something to gain by the success of its research programs, and is mainly constituted of companies in the steel and automotive industries. Other sponsors include galvanizing line equipment manufacturers, suppliers of post-treatments and galvanizing bath hardware, manufacturers of welding equipment, and others. IZA welcomes suggestions for candidate sponsor companies from existing GAP members that will allow a more valuable program to be developed.

Table II. 2017-2019 GAP Program Sponsors

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<tr>
<th>Steel Companies</th>
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<th>Automaker</th>
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II. INTRODUCTION

The Galvanized Autobody Partnership (GAP) was established as a program of International Lead Zinc Research Organization, Inc. in 1999 to help retain and grow the market for galvanized steel sheet and automotive bodies and structures by technical innovation. Since this time, ILZRO has merged with International Zinc Association (IZA). It is anticipated that the GAP program will be continued to be operated as a series of 3-year plans following those executed between 1999 and 2019. Each of these programs has been sponsored by collaboration of steel and automotive companies, together with suppliers in partnership with these sponsors.

As part of its objective, the GAP program seeks to support the steel industry in its efforts to maintain and enhance steel-based automotive solutions as the dominant means by which automobile bodies and structures are manufactured. This is supported through technically innovative programs whose results are transferred to sponsors during semi-annual program review meetings, reports and other documentation. Fleet carbon dioxide emissions performance regulations in many countries continue to become stricter with time. Figure 1 shows historical fleet carbon dioxide emissions performance, showing historical performance, together with future plan standards. The grams of CO\(_2\) emissions per kilometer are normalized, according to the NEDC (New European Driving Cycle) test standard. Most of the standards shown are for light-duty vehicles (LDV), http://multibriefs.com/briefs/exclusive/automotive_lightweighting_trend_1.html
For the overall European Union, historical performance has improved CO₂ emissions from 170 grams CO₂ per kilometer to 140 between 2000 and 2010. These are expected to decrease to 95 grams CO₂ per kilometer by 2020. In the USA, ex-California, the fleet has an average performance of 260 grams CO₂ per kilometer in 2000. This decreased to 220 in 2010 and further decreased to 170 in 2016. USA regulations, ex-California, if preserved, would reduce this to 107 grams CO₂ kilometers in 2025. Canadian performance is slightly better than USA, reducing from 249 grams CO₂ kilometers in 2000 to 205 grams CO₂ per kilometer in 2010. In South Korea, the earliest date for which data are available is 2004, where fleet emissions were 231 grams CO₂ per kilometer, reducing to 190 in 2010. Japanese performance is slightly better than the EU, beginning at 170 grams CO₂ per kilometer in 2000, reducing to 130 in 2010.

The U.S. Corporate Average Fuel Economy (CAFE) mandate, requiring fleet fuel economy of 54.5 mpg (4.3 L/100 km) for passenger vehicles and light trucks, will become the prevailing limit in the USA in 2025. There has been a gradual increase from the 2010 level of 25 mpg (9.4L/100 km) to 34.1 mpg in 2016. This is an average of requirements for passenger cars and light trucks with gross vehicle ratings of 8500 lb (3856 kg) or less. If an automaker does not meet this standard, the manufacturer must pay a penalty, currently $5.50 per 0.1 mpg under the standard, multiplied by the manufacturer’s total production for the U.S. domestic market. All of these mandates have driven both steel and its materials competitors to accelerate development of materials and design solutions for bodies, structures and power train that will allow this fuel economy standard to be met.

The proposed GAP program addresses the highest-priority research and development issues relating to production of galvanizable steels in support of these lightweighting efforts. Five of the twelve programs from the 2017-2019 GAP Program are continuing into 2020-2022. These continue to be dynamically redirected as a result of semi-annual review at the GAP Program Review meetings and therefore the proposed continued work in each of these reflects new challenges that have arisen in the meantime, rather than being straightforward continuations of previous programs. The seven new programs are based on priorities that have been agreed to by 2017-2019 GAP sponsors to meet evolving challenges, such as the increased fuel economy mandates described before.

Two large programs focus on families of steels that have already become important for lightweight automotive construction: third generation (austenite-martensite) advanced high strength steels and press hardened steel grades. Our work on third generation steels has focused on 6% Mn steels, with varying amounts of Si, Al and other alloy elements that allow the US Department of Energy third generation steel goals to be met with Zn-coated steels. The very fine grain structures of these grades permit both TRIP (Transformation Induced Plasticity) and TWIP (Twinning Induced Plasticity) mechanisms to be operative, producing very high combinations of strength and ductility. The relatively low intercritical annealing compositions required for these grades prevent surfaces to be produced that can be hot dip galvanized.
In the hot press forming program, the minimum level of Zn required in Zn-Fe hot press formed coatings to provide sufficient galvanic properties to provide sacrificial corrosion to automotive steels has been determined. Basic research on microcracking in hot press formed Zn-coated steels has also continued. Two new higher-Mn hot press forming grades, that can be processed to avoid liquefaction that is related to microcracking, have also been developed and are currently being characterized in the program. Two new programs in Focus Area I have been developed in accordance with sponsor priorities. One is investigating decarburization issues in advanced high steel processing. Decarburization in this case is related to the higher dew points that are required to prevent external oxidation of high strength grades as they are processed for hot dip galvanizing. The second new program is investigating factors that influence coating adherence on advanced high strength galvanized steels. The common way of investigating steel-coating reactions during galvanizing is wettability; however, this is found to be only indirectly connected with adherence. The fundamental information related to wettability phenomena must be related to the practical observations made on adherence of galvanized coatings that are important for formability and user-related issues such as dent resistance.

Processing issues will be continued to be supported in Focus Area II. One program continues form the 2017-2019 GAP Program that is investigating the effects of steel surface characteristics on emissivity, and how this emissivity is related to strip temperature, using existing and developing pyrometry techniques. The strong dependence of emissivity on strip roughness and details of surface oxides and how this relates to the wavelength(s) of the pyrometer being used for temperature measurement are all significant. Further information will improve our accuracy of temperature measurement. Three new programs will also be initiated. The first, on coating weight stabilization, will continue development of an improved multi-slot coating control knife that will be coupled with state-of-the-art strip stabilization techniques. This work will also include work on Zn-Al-Mg coating weight control development. The second program continues our work on improvement of galvanizing bath hardware. Pot hardware issues are still one of the largest causes of unscheduled line stoppages. The new work will focus on dross buildup in pot roll grooves. The third program will take a more fundamental approach to understanding galvanizing dross growth and dissolution. Our past work on galvanizing pot hardware and bath equilibria have uncovered gaps in our knowledge of dross dissolution and growth phenomena that this new program would seek to fill.

Programs addressing performance issues in galvanized automotive steels are included in Focus Area III. Two programs continue: the first will continue to investigate the effects on exposed panel appearance of surface oxides, textures and microstructures originating in prior strip processing steps, beginning with slab reheating, on the quality of galvanneal surface appearance. The second continues work on a very high-priority project for automotive steel: the effects of the Zn coating and steel conditions, together with welding process variables, on liquid metal embrittlement phenomena. Several approaches to minimizing LME have been found in past work in this project, including use of different current-time profiles and electrode shapes. Other
directions will continue to be investigated. The third project will be a new initiative on details of coating microstructures and coating thickness influence performance of alloyed coatings, especially for Zn-Al-Mg coatings. Although compositions of this family of coatings all lead to similar performance and overall corrosion performance and formability, past work has indicated notable differences that relate to the fineness of the microstructure in the overall coating thickness. The final program will be a new initiative on non-fusion joining techniques, specifically related to gas metal arc brazing. Higher strength steels result in more significant welding issues than their predecessor low strength grades and many of these issues are now being met by not melting the steel but rather joining by the non-fusion brazing process. The new project would investigate the most important issues that have been identified based on industrial work to date.

The previous GAP program structure of 3 Focus Areas, each containing 4 multi-year programs, has served well and is utilized for the new program. The programs proposed for 2020-2022 were subject to zinc and steel industry review at the GAP Program Review Meetings in May 2019. Comments made during and after discussion of the programs at these meetings are reflected in the meeting Minutes and have been taken into account in development of the program plans contained in this catalog.

The proposed 2020-2022 GAP Program is shown in Table III. A total effort of about $645,000 per year, or $1,930,000 in total for the 3-year GAP Program is proposed, using cash sponsorship only from GAP sponsors. These will be augmented by outside funds, including commitments from national governments, other industry associations and miscellaneous sources. We believe the funds proposed will allow the proposed programs to be carried out in an efficient and timely manner.

Sponsors automatically receive all reports and publications resulting from the programs they sponsor and also have the possibility to hear about the progress of other GAP programs during the Program Review Meetings. The results are also briefly summarized in quarterly reports sent to members.
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<tr>
<th>Program Number</th>
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III. OVERVIEW OF WORLDWIDE AUTOMOTIVE STEEL INDUSTRY DEVELOPMENT

As indicated before, increasing fuel economy regulations in the USA and Europe have posed significant challenges to the worldwide automotive industry and are expected to influence the selection of materials of construction for automotive bodies. Both the USA 54.5 mpg-by-2025 Regulation (107g CO$_2$/km by 2025) and the EU 95 gCO$_2$/km by 2020 goals have necessitated strong new initiatives in the automotive steel industry, together with its competitors in the aluminum and carbon fiber industries, each of which is offering solutions to light-weight vehicle construction to meet these new requirements. Moreover, multi-material solutions are being used in several upper-tier passenger cars, despite the increase in costs of using multi-material solutions.$^2$

In the USA, the achievement of the target fuel economy regulations is expected to require a reduction of average vehicle curb weight by 460 pounds (208 kg), or 12%, from the 2008 base line to 2025. This ranges from the weight reduction of 280 pounds (127 kg) for small cars up to 750 pounds (340 kg) for large and medium trucks and SUV’s. It is expected that this should be done without sacrificing size or functionality and without significantly reducing costs.$^3$ The steel industry has maintained its dominance by revamping manufacturing processes and bringing new steel grades to production. More importantly, the steel industry has worked with its customers on holistic, cost-saving processes to realize fuel economy goals without significant new costs. However, the aluminum industry has realized successes in its challenge to steel as the primary material for aluminum body structures and exterior panels. The highest volume example of their success is the conversion of the Ford F-Series pickup truck line to an aluminum-intensive body and cargo box in 2015. Two assembly lines now produce 700,000 units per year of the F-150 model. The F-250 and higher Super Duty versions of this truck are produced on a third assembly line. The F-250 model is 350 pounds (159 kg) lighter than the previous version, which was last redesigned in 1999. This includes the weight savings achieved by use of a fully boxed advanced high-steel frame that supports the aluminum body.$^4$ Other important, but smaller volume car line conversions have included Jaguar and Rover vehicle bodies.

Multi-material automotive platforms are also emerging. A leading North American example is the 2015 Acura N5X model that uses a composite dual phase steel/press harden steel aluminum die cast A-pillar structure to improve visibility and reduce weight.$^5$ The composites materials industry is also investing strongly in automotive materials, the BMW 7 Series includes a combination of steel, aluminum and carbon fiber reinforced plastics. Several components, including the door sills, are either reinforced or replaced with carbon-reinforced plastic panels.$^6$ The USA Department of Energy Multi-Material Lightweight Vehicle (MMLV) program funded many projects allowing for design, build and testing activities that validated several advances in automotive structural lightweighting. These included several designs that incorporated steel, magnesium castings and aluminum extrusions. Galvanic protection was addressed in many cases by pre-painting these components before joining them into an assembly.$^7$
Automotive safety requirements, especially for crash requirements, continue to become more stringent, imposing additional demands on automaker designs. The recent small overlap front crash tests conducted by the Insurance Institute for Highway Safety (IIHS) introduced a very significant challenge, with only 25% of the vehicle front end striking a barrier at 64 km/h. This test, together with others, requires steels that both maintain the shape of the safety cage for occupant protection but also significant energy-absorbing components in the vehicle designed to reduce occupant and pedestrian injuries. These therefore require a variety of steel characteristics to meet these performance requirements. Although these tests are always carried out on new vehicles, the ability of vehicles to meet these crash performance requirements after a number of years of service can be questioned. The continued use of corrosion-resistant coatings in vehicle bodies and structures should maximize the ability of today’s vehicles to meet safety scenarios after many years of service.

In 2018, total motor vehicle production worldwide was 98.1 million units, an increase from 2015 that saw 95.1 million units produced. Of this, 29% was produced in China, including Taiwan; 23% in Europe; 18% in North America; 14% in Japan and Korea and 10% in South Asia. 3.5% was produced in South America and 2.6% in Middle East/Africa. Here, Europe includes both Turkey and the CIS countries.

Because of the increased use of thinner advanced high strength steels and ultra-high strength steels, as opposed to mild- or high-strength steels, the mass of steel in the typical North American light vehicle will decline by 65 pounds (29.4 kg) between 2018 and 2020. Overall, steel will make up 53% of overall curb weight in 2020 versus 54% in 2018. Aluminum will hold steady, at 9%. The curb weight in 2020 is forecast to be 3735 pounds (1694 kg), versus 3790 pounds (1719 kg) in 2018. The use of advanced high strength steel and ultra-high strength steel has grown significantly since 2013, from 209 pounds (94.8 kg) to 329 pounds (149.2 kg), translating to an average growth rate of 20 pounds per year (9.1 kg/y). At present, ultra-high strength steels make up only 5% of the body-in-white and closure mass; however, this is expected to grow to 28% by 2025. Press-hardened steels are currently used in A and B pillars, together with door rings, headers and beams, and also in the rocker support and reinforcement. Tunnel rails, bumper beams, floor sills, hinge posts and cant rails (roof frames) are other applications where hot press formed steels are being adopted. Advanced high strength steels, which include dual phase, TRIP, TWIP and third-generation steels, will grow from 17% of body in white and closure mass in 2018 to 22% in 2025. These parts are able to be used for advanced geometries with complex shapes. As properties of third generation steels improve, they are expected to replace current applications of press-hardened steels if they can deliver the performance characteristics. Suspension arms and lengths, sub frames, cross members and instrument panel structures are all candidates for third-generation steels.

A drawback to the increased use of press-hardened steels has been the limitation on galvanic protection available to vehicle components, especially those closer to the road, because of the low Zn content in the coating after the press hardening operation. During our 2017-2019 GAP
Program, it was concluded that a press-hardened coating must contain at least 15% gamma phase in order to provide meaningful galvanic corrosion protection to the steel. A microcracking issue has now largely been solved by controlled deformation and cooling, so that the most severe deformation occurs after no liquid is present in the work place during drawing deformation. Controlled-process, direct hot stamping with a Zn coating is now fully industrialized.\textsuperscript{11, 12}

During recent years, significant improvements in continuous galvanizing lines have been made. These include the use of supervisory control for all units of the lines, individual advanced controls for coating control sections, including advanced feedback, strip stabilization to minimize overcoating, the use of advanced bearings and coated rolls in pot hardware and improved heating and cooling schemes in the pretreatment furnace and also the availability of overageing sections on several lines.\textsuperscript{13} Improved atmosphere control through the zones of the furnace has also been greatly improved to allow for processing of advanced steels. In particular, the introduction of direct flame impingement heating sections prior to subsequent heating to annealing temperatures, and the use of oxidizing sections within heating and soaking sections without use of open flames has permitted the development of internally-oxidized conditions within advanced high strength steels that enable Zn coatability. These areas are expected to receive continued technical support in the 2020-2022 Galvanized Autobody Partnership Program as the challenges of new steels and coatings continue.

IV. ACCOMPLISHMENTS OF 2017-2019 GAP PROGRAM

a. Focus Area I – Galvanizing High Strength Steels for Lightweight Automobiles

\textbf{ZCO-65, “Hot Dip Galvanizing of Third Generation (3G) Advanced Steels”}
This program at McMaster University is examining hot dip galvanizing of this new class of steels that is expected to have high contents of martensite and stable austenite. The project is focused on high Mn TRIP steels with Mn contents around 6%, together with Si contents between 1-2% and Al between 0.1-2%. Small amounts of Sn are being added to improve surface activity. These steels produce mechanical properties in the range demanded by the US Department of Energy and USA automakers; for example, Steel D in this program gave a yield strength of 1190 MPa, and a tensile strength of 1200 MPa with 22% total elongation. These can be processed with intercritical annealing temperatures below 700°C which limits the amount of surface selective oxidation that can occur, improving galvanizability. A total of six steels are under current investigation. A significant award from National Science and Engineering Research Council of Canada allowed for significant expansion of project activities.

\textbf{ZCO-62, “Oxidation Phenomena in Advanced High Strength Steels.”}
This program at University of Delft continued without new funding in 2017-2019 and is expected to conclude at the end of 2019. It is conducting both theoretical modeling and experimental characterization of oxidation and related phenomena in high strength dual phase steels that influence galvanizability. Together with characterization of the steel’s response to
galvanizing treatments, the surfaces and interfaces of these steels prior to and after hot dip galvanizing has been examined in great detail. De-wetting experiments using a liquid lead model alloy have also been carried out, allowing evaluation of the contact angle and work of adhesion.

This project at McMaster University defined the microstructural and electrochemical properties of press-hardened steels with Zn coatings to determine the range of product and product characteristics that gave suitable galvanic protection for automotive body applications. As noted before, this means that at least 15% gamma phase must be present in the coating. The origins of microcracking in Zn-coated press-hardened steels are currently being studied. Two higher-Mn compositions with lower processing temperatures that allow the Zn to be in a solid state during deformation processing have also been developed. Work on the lower Mn content grade of the two is well advanced. This project also benefited from a significant award from the National Science and Engineering Research Council of Canada.

ZCO-75, “Nature of Galvanizing Wettability in Advanced High Strength Steels.”
This program at Centre de Recherches Metallurgiques is examining the effects of higher dew point pretreatments, together with an oxidation pretreatment step, in evaluating wettability behavior of two dual-phase steels and a TRIP steel, together with an IF reference composition. The nature of the inhibition layer is also strongly related to wettability, where a strong and sharp Al peak at the interface is coincident with good wettability. The influence of the pretreatment routes taken also influences the nature of the inhibition layer, the wetting angle of the liquid Zn coating on the treated steel and the coating adherence.

ZCO-76, “Hydrogen Behavior and Effects on Advanced High Strength Steels.”
This program at Centre de Recherches Metallurgiques is extending past work carried out at this institution for the GAP program. Work conducted in that program has been validated and several new tasks undertaken: the effect of jet cooling on hydrogen uptake, the effect of galvannealing on hydrogen uptake and the effect of coating composition, notably Zn-Al-Mg compositions, on hydrogen uptake. This behavior is being studied with DP980, TWIP and TRIP780 compositions. Mechanical properties testing will be carried out to conclude the program.

b. Focus Area II – Improving Quality of Hot Dip Coatings

ZCO-56, “Improving Coating Weight Efficiency.”
This project at McMaster University has greatly extended our knowledge on the behavior of single- and multi-slot air knives with regard to the nature of the wiping jet vorticity and related wiping force and sonic phenomena that occur with normal industrial production. Substantial
experimental and computer modeling work has given much guidance to process optimization. A PhD thesis that will provide fundamental understanding of the nature of unsteady flow effects on coating quality and jet stability is being completed.

**ZCO-57, “Improving Galvanizing Bath Hardware.”**
This program at Metal Center Leoben/University of Leoben provided valuable insights into the nature of the dross buildup phenomenon on moving pot rolls in the galvanizing bath. Modeling of the temperature composition and fluid flow fields into the vicinity of the moving pot roll confirmed long-standing observations that strong competitive growth occurs in dross particles as they build up on the roll, reducing to very large dross particle sizes on moving rolls in comparison with stationary components. Dross growth is most significantly influenced by the vertical component of flow, normal to the roll surface so that the nature of growth changes as dross buildup progresses. This is related to the nature of the more severe turbulence that is induced when rough surfaces are created by the growing dross.

**ZCO-77, “Dross Minimization in Galvanizing Baths.”**
The origins of top skimings on the galvanizing bath are explored in this project at National Research Council Canada. Existing wiping gas jet models have been modified to study the flow of fugitive gas downward on the strip toward the surface of the Zn bath, after which the gas continues flowing across the surface of the galvanizing bath. The nature of surface instabilities; i.e., ripples, on the surface of the bath greatly contributes to dross formation. Significant efforts were also expended on collecting dross generation data from industrial lines. Although a great deal of data were collected, it was not possible to produce a physically valid model because of the different means and schedules by which dross samples were collected. A phenomenological model was therefore used to improve our knowledge of how dross skimings are influenced by galvanizing bath process conditions. Work will conclude by development of a Zn-Al-Mg dross formation model.

**ZCO-72, “Surface Profile Effects on AHSS Processing.”**
This joint project at University of Waterloo at Ecole de Polytechnique de Montreal is investigating the effects of surface features on advanced high strength steels on emissivity, and how the measured emissivity is related to surface temperature. Surface conditions are mainly related to surface roughness and the nature of surface oxides on the steels. The surface roughness scale influencing emissivity has been found to be much finer than expected, on the order of hundreds of nanometers, rather than the micron-scale typical of cold rolled steel roughnesses. The effects of temperature deviations caused by temperature inaccuracies on the mechanical properties of the processed steels has been investigated. All of this work is supporting the next stage in the expected program, which will be to develop industrial tools.
aligned for more accurate temperature measurement. The program is well-supported by industrial partners and also a grant from the National Science and Engineering Research Council of Canada.

c. Focus Area III – Performance of Galvanized Automotive Steels

**ZCO-45, “New Zinc-Based Automotive Steel Protection Technologies.”**
This program continued from the 2014-2016 GAP Program without additional requirements for funding. Its purpose was to conclude a two-year outdoor exposure program at French Corrosion Institute on various Zn-Al-Mg-based coated steels, several of which had quaternary additions intended to improve corrosion resistance. Long-term corrosion testing showed that the Si-containing Zn-Al coatings showed better corrosion stability and protection of the exposed coating-steel interface than the ternary Zn-Al-Mg alloy. Unpainted hem flange specimens showed similar improvements in corrosion performance for the Si-containing composition and a poor performance of the Ti-containing compositions. Conversely, for painted samples, a slightly better performance was seen with the Ti-containing coatings. However, for the painted samples, one year of outdoor exposure was too soon to allow a ranking of the different coating systems. Several samples are being kept on exposure for later removal.

**ZCO-74, “Examination of Zinc-Coated ‘Sandwich Steel’ Construction.”**
This project at University of Clausthal investigated the production of carbon fiber core/dual-phase steel outer skin samples that have the potential of being much stiffer than monolithic steel panels. These will be useful for improving dent resistance in closure applications, among other applications. The fabrication process was found to be very sensitive to details of processing, and the best results were found by using a dielectric barrier discharge (DBD) surface treatment technique that uses a non-thermal plasma. The graphite could not be induced to bond directly to the steel and therefore a precursor adhesive, 3-aminopropyltriethoxysilane (APTES) was used, together with trials involving several other precursors. The APTES layer was found to give the best results, giving a mixed fracture with both cohesive and adhesive fractures. The interface was found to be more stable than the core material and a good peel resistance was realized. The time between plasma treatment and application of the precursor was another critical variable.

**ZCO-78, “Influence of Surface Oxides, Texture and Microstructure on Quality of Galvanneal Surface Appearance.”**
This project at Colorado School of Mines investigated the nature of defects on several galvannealed and one galvanized (GI) sample received from sponsors. Several uncoated companion samples were received, from various stages of production. The nature of mill scale on the surface of the precursor samples was related to several of the defects, while a periodic defect appeared to be related to the nature of roll grooves on the galvanizing line sink roll. The GI defect was concluded to be related to splashing during the coating control section. It is
expected to continue this program in the 2020-2022 GAP Program to allow for an investigation of more varieties of samples.

**ZCO-79, “Internal Oxidation Effects on Forming and Welding Behavior of Advanced High Strength Steels.”**

This program at University of Waterloo and McMaster University investigated the effects of internal oxidation pretreatments on the stability of resistance spot welding of the steels. The relative degrees of internal and external oxidation in these dual-phase compositions, which contain varying levels of Si, was found to influence the geometry of the weld lobes that were produced during welding trials and also the strengths of the welds. Resistance spot welding was conducted on both similar metal joints and also stack-ups using the different types of steels that were studied in the program, each with different amounts of internal and external oxidation produced by variations in the galvanizing pretreatment cycle. This program also benefitted from supplementary funding from the National Science and Engineering Research Council of Canada.

**ZCO-80, “Zinc Effects on Mechanical Behavior of AHSS Welds.”**

This program at University of Waterloo focused on the nature of liquid metal embrittlement in high-austenite steels, using a variety of dual-phase and TRIP steels with retained austenite contents up to 16%. Experimental and modeling work was carried out that produced a cracking index that was thought to be more reliable than past measurements of LME. This was used to gauge the results of process variations studied in this program. Multi-pulse and pre-pulse welding patterns were observed to reduce LME cracking and this was found to be related to diffusion of Fe into the coating before melting of the steel. When this technique is used, it is necessary to obtain a balance between the amount of Fe-Zn alloying and the heat input required to melt the nugget. Use of a ramp downcurrent was also shown to reduce LME cracking, by allowing the nugget and surrounding steel to gain strength before removal of the electrode. Finally, studies of different electrode tip geometries indicated that a low-radius tip produced much less LME cracking than a dome or truncated cone electrode. This was related to the nature of thermal stresses on the weld shoulders. This program is expected to continue in 2020-2022.

**V. OVERVIEW OF PROPOSED 2020-2022 GALVANIZED AUTOBODY PARTNERSHIP PROGRAM**

**a. Focus Area I – Galvanizing High Strength Steels for Light Weight Automobiles**

Two programs will continue from the 2017-2019 GAP Program, while two of the programs are entirely new. The continuing programs are concerned with improving performance of galvanized steel with high-priority families of steel grades: third generation advanced high strength steels and hot-pressed formed steels with Zn coatings. The first of the new programs is investigating the nature of decarburization in advanced high strength steels that are expected to influence local formability and other user properties of advanced high strength steels. The
second is investigating the nature of adherence of the Zn coating to advance high strength steels, distinguishing it from wettability. Both wettability and adherence are used to assess the nature of the quality of the Zn coating on the steel; however, it has become clear that their relationship is complex, and in some cases the results of wetting and adhesion tests are not correlatable.

**ZCO-53, “Hot Dip Galvanizing of Third Generation (3G) Advanced Steels.”**
This program will continue its investigation of the hot dip galvanizability of selected compositions in this new class of steel, continuing its focus on 6% Mn-Si-Al compositions that have been able to meet Department of Energy property requirements. Two important details are expected to influence mechanical performance of these steels after they leave the galvanizing line and are related to the complex nature of static and dynamic strain aging that occur in these compositions. Samples will be aged and otherwise processed to simulate forming and heat treatments such as paint baking that are typically used during automotive manufacturing to determine their effects on mechanical properties.

As indicated before, this project to date has successfully indicated the ranges of Zn content that are required for galvanic protection to be provided to Zn-coated hot press formed steels, is investigating the nature of microcracking in these steels and also the utilization of higher Mn compositions that allow lower processing temperatures to be used. Work will continue by providing further information on the behaviors of these two high-Mn steels and also examining tailored cooling of hot-press-formed parts, taking a fundamental view to determine the effects of tailored cooling on variations in microstructure and the hot-press-formed coating.

**ZCO-81, “Decarburization Issues in AHSS Processing.”**
Use of higher dew point pretreatments that allow for internal oxidation to be produced in steel substrates prior to galvanizing are also known to be related to decarburization phenomena. These phenomena are expected to influence steel properties, especially when decarburization occurs over depths of more than 1 micron. This program would investigate the limiting steps for this decarburization phenomenon, which is either related to the surface fraction of oxides that block transport of C from the bulk of the surface or the steel details that determine the rate of C diffusion through the bulk and near-surface steel volume. This will be related to mechanical properties, notably local elongation effects such as hole expansion ratios.

**ZCO-82, “Improving Zinc Coating Adhesion.”**
Normally, a well-wetted Zn coating on a steel substrate is assumed to be well adherent; however, there are many cases encountered in processing an evaluation of galvanized advanced high strength steels where this is not the case. This project will investigate several means of improving adherence of the Zn coating to the steel, including the nature of local saturation of elements in the galvanizing reaction, the role of surface active elements on coating adhesion and
influences on the development of the interface, which is normally iron aluminide for the GI coating. Work will also be extended from GI to Zn-Al-Mg coatings.

b. Focus Area II – Improving Quality of Hot Dip Coatings
Only one of the prior projects will continue in the 2020-2022 Program, the study of the effects of steel surface details on emissivity and therefore accuracy of temperature control in the galvanizing pretreatment furnace. The three new projects will deal will deal the validation of prior coating control work carried out in the GAP program, undertake a new approach to studies of dross buildup in bath hardware roll groves and embark on a fundamental study to fill some of our fundamental gaps in understanding of the nature of dross dissolution and growth.

ZCO-72, “Surface Profile Effects on AHSS Processing.”
To date this project has investigated the nature of surface roughnesses and surface oxides on emissivity properties of several DP steels with varying Si contents. The scale of roughness influencing emissivity was found to be smaller than originally anticipated, on the order of nanometers. The wave length of emissivity measurement used to obtain temperature readings has also been found to be much more critical than known before, and over a different range than originally anticipated. The effects of temperature deviations on mechanical properties obtained in these steels has also not been straightforward, due to the types of phases, notably different morphologies and volume fractions of martensite and bainite, that have been encountered in the processed steels. This project will continue to gain a further understanding of the relationships between the surface properties of the selected advanced high strength steels that are known to effect emissivity. This will include an extension of our investigation of surface roughness characteristics over the range of importance and the nature of oxide distributions on the surface of these steels. The effects of these on emissivity, and development of an algorithm for relating these to temperature readings, is also an essential part of the program. The effects of these temperature deviations on mechanical property deviations will also continue to be investigated.

ZCO-83, “Coating Weight Stabilization.”
Our past work using both single-slot and multi-slot air knives at McMaster University has been very successful in developing models of the nature of vorticity and how this affects jet stability, and therefore consistency in coating weight. Jet instability is also closely linked to the nature of noise encountered near the wiping apparatus. It is now time to move from the laboratory with this project to an actual industrial validation. This is expected to use one of the state-of-the-art means of strip stabilization now being used industrially, together with the optimized knives developed in this project. This should allow for a stable jet core to be produced at much more reliably, and at larger standoff distances from the strip, than available before, allowing for improvements in coating weight stability. Both air and nitrogen wiping are expected to be used during these trials. The work will be extended to Zn-Al-Mg alloys by a study of properties of these liquid alloys relevant to coating weight control.
ZCO-84, “Dross Buildup in Pot Roll Grooves.”
Our past work with dross buildup has indicated how the nature of growth of dross in a moving roll is very different than that on a stationary part. This is related to the nature of turbulence that is developed after dross growth begins to occur and the competitive growth that allows only large crystals to be produced. The pot roll groove environment is quite different from that of the exposed roll surface. Modeling of the roll groove environment, together with industrial validation of the results, is expected to provide similar insights into the nature of dross buildup and means of minimizing roll groove dross effects on coated strip quality.

ZCO-85, “Kinetics Growth and Dissolution of Galvanizing Drosses.”
Our work on top skimmings, pot hardware dross buildup and past studies on dross dissolution and growth in the galvanizing bath from prior GAP programs have all shown the need for additional fundamental information on the nature of dross dissolution and growth mechanisms. This project will take a fundamental look at the kinetic coefficients relating to the nature of growth. These have much to do with the geometry of each of the different dross crystals, including Al-Fe and Fe-Zn chemistries, together with the surrounding conditions of temperature, composition and flow surrounding the dross particle as it grows or dissolves. Experimental and theoretical modeling work would extend our information, making future industrially-related simulations more accurate.

c. Focus Area III – Performance of Galvanized Automotive Steels
This focus area includes one continuing project that is relating the nature of GA defects to substrate defects arising from various flat rolled processing steps along the way to production of coated steel strip. The second continuing project is our high-priority project on liquid metal embrittlement effects occurring during resistance spot welding of seals containing relatively high amounts of retained austenite. Two new projects are included that will study the effects of microstructural details in Zn-Al and Zn-Al-Mg coatings on performance and also factors influencing the successful processing of raised joints made from advanced high strength thick-coated steels.

ZCO-78, “Influence of Substrate Oxides, Texture and Microstructure on Quality of Galvanneal Surface Appearance.”
This project at Colorado School of Mines has related several details of flat rolled steel processing, beginning with slabbing and moving through hot rolling to cold rolling, for several samples of galvanneal and one GI-coated steel. It has been successful in linking upstream effects to the galvanneal defect that has been observed in several cases. It is expected to continue this project by collecting additional samples from sponsors, including the galvanneal coating with the
defect to be studied, together with precursor uncoated flat strip, together with hot strip mill product and samples of slab, where relevant. Increasing the scope of this study will allow for a sounder scientific basis to be developed for remediation of these defects.

**ZCO-80, “Zinc Effects on Mechanical Behavior of AHSS Welds.”**
This program at University of Waterloo has investigated the effects of different weld electrode geometry and current pulse effects on the incidents of LME cracking in advanced high strength steels with various retained austenite contents up to 16%. This investigation will be continued by looking at the role of specific starting microstructures on LME sensitivity and focus on the origin of several specific crack geometries that are poured for LME. The influence of coating type on the severity of LME will also be investigated. The mechanical performance of spot welds produced with each of these experimental variations will also be evaluated, including cross tension shear testing.

**ZCO-86, “Zinc Alloy Coatings Microstructure and Coating Thickness Effects on Performance.”**
Alloyed coatings, mainly Zn-Al-Mg compositions, are beginning to be adopted for automotive applications because it is believed they can be used at lower coating weights, improving formability and welding, while having at least the same corrosion performance as traditional Zn coatings. However, the reduced coating weight allows for the microstructural heterogeneities in alloyed coatings, especially the difference in phase compositions between the primary Zn and higher alloyed phases, to play a more important role in performance. The effects of these different phases can be controlled by higher cooling rates; however, their effects on performance have just begun to be studied. The overall coating weight and microstructural fineness also influence the nature of protective surface compounds that are formed on the hot dip coated sheet as it cools, influencing further processing effects and corrosion performance. This project would evaluate coatings with a range of microstructural features expected from industrial production, including the Zn-Mg phases that have been observed in investigations to date, together with a range of coating thicknesses that are currently or likely to be produced in the future to determine the effects of these variables on corrosion and forming performance.

**ZCO-87, “Interface and Performance Issues in Non-Fusion Joining of Zinc-Coated Steels.”**
To overcome the issues encountered with welding of advanced high strength steels caused by their melting and re-solidification in the weld nugget, brazing has been adopted, especially for seam welding of joints involving these steels. Issues relating to wetting and flow of the brazing material, together with its related reaction with the Zn coating and the underlying steel, have only been investigated in short-term investigations, and always on lower-strength steels. This project will take a broader examination of the principal factors affecting brazing qualities of Zn-coated advanced high strength steels, focusing on the gas-metal arc (GMA) brazing process.
The different GMA methods of braising, including short circuit, pulse and other methods would be investigated, together with various types of filler wire that are possible to use.

VI. GAP OPERATING POLICIES AND PROCEDURES
Policies and procedures to be followed in the Galvanized Autobody Partnership will be similar to those developed for operation of the previous GAP programs. After determination of final sponsor contributions for each program, a final program budget will be settled and allocation of available funds among planned projects will be determined with sponsors. Request for Proposals will then be sent to sponsors for approval and a list of potential investigators agreed to. The Request for Proposals will then be sent to each candidate investigator and received proposals will be sent to sponsors for balloting. IZA will then contract with the chosen investigator. Formal Research Contracts are always used and typically give IZA and its sponsors rights to any developments arising from the research. The only exceptions are made in the case of university-based research, where fellowship grants may be used.

Program Review Meetings are a very important element of the GAP program and are held several times each year in Europe, North America and China. There is potential to have such meetings held in other regions of the world if wide sponsorship of such programs evolves in such regions. Sponsors in other regions are always notified of upcoming Program Review Meetings well in advance and are welcome to submit comments if they cannot attend these meetings.

Program Review Meetings offer an opportunity to discuss the most recent results arising from each program along with proposed work for the future. The meetings offer sponsors an opportunity to help direct the program to meet the objectives of each company. A consensus is always sought between sponsors and harmonization of recommendations made by program review meetings in different regions is sought by IZA. Outstanding issues are usually settled by balloting or other correspondence with worldwide sponsors.

Another important function of the Program Review Meetings is to provide a forum for discussion of related topics between attendees, including the possibility for informal meetings among the procedures themselves.

The GAP program is intended to be “open” in nature so that all research results will be made available to all members attending program review meetings as well as non-members after a period of time, usually one year, if patents are not forthcoming. However, written progress reports from the investigator are only mailed to those companies who actually sponsor each program. Other companies receive summaries of progress during the program review meetings, and reports of these meetings. Members are encouraged, but not required, to share relevant technology and experimental samples to further the research goals of this partnership. Unique technological discoveries may be patented and licensed by ILZRO to partnership members at a preferential rate, and on a priority basis with respect to time, compared to non-members.
As a principal objective of this partnership is to grow markets and applications for galvanized autobody sheet, it is the intention of IZA to make the technology resulting from this research program available to all, but to provide an appropriate advantage to sponsors. Sponsors will have the advantages of being involved in the planning and direction research and also have immediate access to results, and can join in discussions regarding policies regarding proprietary results and patenting issues as they arise.

This partnership may support the development of patented technologies; however, such technologies will only be included in research programs if IZA sponsors can have access to the patents for a reasonable, preferential fee, which must be agreed to prior to either providing sponsorship or including the proprietary information in the scope of any research program.

Research findings and flow of information shall be made available to sponsors through review meetings and semi-annual reports. Sponsors have the right to a return of contributions or promises of contributions on an annual basis if IZA fails to complete review meetings or provide semi-annual reports. Upon completion of each annual period, IZA unconditionally retains rights to funds contributed or promised.

The primary planning, program direction and technology transfer mechanism for the GAP program is the program review meeting structure. Therefore, all sponsors are urged to attend the program review meetings. In addition, a comprehensive review of these programs has been given at the IZA Technology and Market Development Meeting, conducted for the zinc industry as part of its review of all programs sponsored by the zinc industry. As the role of the GAP program review meetings has grown, these zinc industry reviews have become more cursory in nature.

Ultimate authority over the operation of the Galvanized Autobody Partnership is vested in the IZA Board of Directors. Day-to-day administration and research management is provided by IZA staff. As part of providing these services, IZA includes in each program cost a “program consultancy fee” which, at present, is 20% of the total program cost. This percentage has been in effect since 1986 and pays for program associated activities of IZA, including funding of the program review meetings.

VII. REFERENCES


ZCO-53 PROGRAM PLAN

“Hot Dip Galvanizing of Third Generation (3G) Advanced Steels”
Issued August 2019

I. OBJECTIVE
This program is examining the hot dip galvanizability of third generation advanced high strength steels containing high contents of martensite and stable austenite. Successful routes for galvanizing and production of targeted mechanical properties in steels with around 0.2 C, 6% Mn, 1-1.5% Si and 0.5-1.5% Al with some with minor additions of Sn to influence surface characteristics, have been produced and tested in the program to date. A major grant from National Science and Engineering Research Council of Canada has allowed this program to continue until mid-2021. It is proposed that this work continue until the end of the 2020-2022 GAP Program by examining ways of optimizing two important details of mechanical performance of these steels: understanding of mechanical properties as these steels pass through the fabrication and assembly steps of automobile manufacture and reduction of strain aging.

II. ECONOMIC INCENTIVE

Third generation steels offer a more economical combination of high strength and ductility than the more highly-alloyed second generation steels. For example, a recent Great Designs in Steel presentation by the United States Automotive Materials Partnership (USAMP) referenced a cost increase of $0.65/kg for 10%Mn steels and $0.53/kg for 35Mn steels compared to cold rolled mild steel, all uncoated. Use of the 3%Mn 3G AHSS to lightweight the body side assembly of a baseline North American 2008 mid-size sedan resulted in a 27.9 kg mass savings; the cost of this weight savings was $0.70/kg.¹

III. BACKGROUND AND CURRENT STATUS:

A total of seven steel compositions are currently being processed and analyzed for influences on mechanical properties and galvanizability in the 2017-2019 GAP program. At McMaster University significant expansion of this program has been enabled by the NSERC award which, for the three projects ZCO-53, ZCO-70 and ZCO-79, has allowed a combined budget of US$921,900 to be provided, of which the GAP program members’ support of this ZCO-53 Program is US$114,345 for the three-year term. In addition to the three tasks on microstructural mechanical property development, selective oxidation, hot dip galvanizing simulation and user property valuations, two additional tasks on phase transformation kinetics of 3G steels and damage and fracture issues in 3G steels have been added. Several steel compositions have been produced that meet US Department of Energy property goals for third generation steels. The nature of the steel surfaces on process steels indicates that these steels will be amenable to hot dip galvanizing.
Improvement and optimization of the steels produced to date will require not only production of satisfactory tensile and total elongation properties, but also yield stress and stability attributes, especially after the steel proceeds from the continuous galvanizing line (CGL) to blanking (including possible tailor-welded blank production) followed by room temperature stamping deformation, usually in several progressive dies, and from there into vehicle assembly and the time-temperature exposures associated with customer usage. These steels will then be expected to provide expected mechanical properties, i.e. in crash testing, at any point in the life of the vehicle, even without consideration of possible corrosion-related issues. This family of steels utilizes both twinning-induced plasticity (TWIP) and transformation-induced plasticity (TRIP) to obtain the high tensile elongations that have been reported. However, the yield strength of TWIP steels is lower, relative to the tensile strength of this family of steels, than other grades of automotive steels. The yield strength of steels investigated is related to the fraction of martensite in the as-produced steel. Therefore, Steel D in the current program, produced with a tempered martensite starting structure and intercritical annealing temperature of 690°C and overaged at 460°C for 120 seconds gave a yield strength of 1190 MPa, together with an ultimate tensile stress of 1200 MPa and a 22% total elongation. This was processed at the lowest intercritical annealing temperature in the experimental plan for this steel. By contrast, Steels A and F, which have similar chemistries, had yield strengths around 900 MPa, with ultimate tensile stresses of around 1300 MPa and total elongations around 19%. These reach their optimum tensile elongation balance with higher intercritical annealing temperatures relative to their experimental plan. Other work has confirmed the relationship of intercritical annealing temperature on yield stress in medium-Mn steels. The yield stress in TWIP-aided steels is known to be very near to the stress that induces twinning. Several approaches to increasing the yield strengths of these steels can therefore be considered. One is the manipulation of the resolved shear stress that causes dislocations to move (plastic deformation). This can include the role of the back stress, which in TWIP-aided steels is a consequence of the localized shear associated with the twin, where the magnitude of the back shear stress is related to the degree of constraint of the adjacent grain. In this way, the imposed forward stress acts on the twins, prompting their twinning response, while the internal back stress acts on the surrounding matrix. Micromechanical modeling in 3 dimensions has now been achieved for several types of steels, mainly dual-phase steels. Another way to increase the resolved shear stress at the onset of plastic deformation is micro-alloying. The use of vanadium has been found particularly beneficial in increasing yield strength of medium Mn steels; it also suppresses the formation of aluminum nitride. Another approach to increasing yield strength is to reduce the overall grain size of the steel. Together with this, the manipulation of the microstructure, into either lamella or equiaxed textures, has also been found to be beneficial. Another approach to increasing yield strength is to impose cold deformation on the as-galvanized product, followed by recovery. This, however, necessitates several process steps after hot dip galvanizing.
Strain aging can be divided into both static and dynamic strain aging. While static strain aging is common in many steels, dynamic strain aging is usually not seen at room temperature in medium Mn steels. However, a pseudo-dynamic strain aging effect occurs with higher carbon medium Mn steels. The manipulation of interstitials in grain sizes can be investigated, using prior microstructure and overageing effects, to minimize overageing behavior.

IV. PROPOSED PROJECT

ZCO-53-3, “Ageing and Stability in Zn-Coated 3G Steel Grades” The objective of this next stage of the project is to understand and predict the actual mechanical properties that selected 3G steels will have in actual vehicle components, after being subjected to the process steps needed to produce those components, and the effects that ageing over the life of the vehicle would have on those properties. The best performing steels arising from the current three-year NSERC-sponsored GAP program will be taken through simulated deformation, assembly and service exposure conditions as described above. They will be aged for various periods of time to simulate user service life. Mechanical tests of interest to sponsors that will likely include tensile and high strain rate testing will them be performed on the processed samples. Microstructures will be examined at points of interest, i.e. after various deformation steps, to analyze the development and changes in microstructural constituents such as retained austenite (and carbon content in the austenite), twins, fraction of martensite and bainite, grain size, textures and details of carbides that are present. The results will be analyzed to consider ways to further manipulate microstructures by processing to optimize yield strength. This can include several of the approaches noted above, including ways of increasing the critical resolved shear stress at the end of elastic behavior. It may include approaches such as micro-alloying and production of very fine grain sizes.

The strain aging behavior of these steels will also be characterized, both static and “pseudo-dynamic”. Ways to manipulate microstructure to minimize strain aging will be sought.

V. COST AND FUNDING SCHEDULE:

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VI. REFERENCES:


ZCO-70 PROGRAM PLAN

Hot Press Forming Process and Product Variables Effects on User Properties
Issued: August 2019

I. OBJECTIVE

Hot press forming (hot stamping) continues to be an enabling technology for production of low-mass steel-based automotive body structures. Successful industrial production with zinc-coated hot press formed grades has now been achieved. The direct hot press forming process for zinc-coated steels consists of blanking, heating, hot press forming at 15 strokes per minute and then shot blasting. The current ZCO-70 GAP Program is examining the microstructural development of \( \alpha(\text{Fe},\text{Zn}) + \gamma(\text{Fe}_3\text{Zn}_8) \) coatings from GA and GI starting materials and is determining the mechanisms of microcracking that can occur using different strain paths. An assessment of cathodic protection potential of these coatings has been completed. To enable processing below the zinc liquefaction (peritectic) temperature of 782°C, two higher Mn steels, with 2 and 2.5% Mn, have been fabricated for testing. A major grant from National Science and Engineering Research Council of Canada has allowed this program to continue until mid-2021. It is proposed that this work continue until the end of the 2020-2022 GAP Program by examining tailored cooling of parts made with these two new steels to determine how properties can be varied as a function of location.

II. ECONOMIC INCENTIVE

Hot press forming of corrosion-resistant advanced high strength steels is a key enabler for the realization of light-weight steel-based automobiles that are expected to meet fuel efficiency and emissions requirements during the next decades. Many hot press formed components are now used in vehicle platforms, and the process is applied to increasingly larger parts, such as one-piece door rings. Direct hot stamping, in which the complete deformation and heating cycle is carried out in an uninterrupted series of steps, was formerly limited to Al-Si coatings but is now in industrial production with GI and GA coatings. It is desirable to improve the performance of Zn-coated hot press formed components for improved quality and productivity using both the indirect and direct hot stamping processes. This will depend on minimization of cracking to acceptable levels while simultaneously providing galvanic protection to the steel substrate by the coating and is expected to involve a systematic investigation of tailored cooling processes.

III. BACKGROUND AND CURRENT STATUS

During 2014-2017, precursor GI and GA coatings over a range of coating weights of interest were processed using hot press forming heat treatment routes to produce a wide range of microstructures and final zinc compositions. It was concluded that a final coating that included a significant fraction of gamma (\( \text{Fe}_3\text{Zn}_8 \)) phase (minimum 15 v%) with the balance being \( \alpha(\text{Fe},\text{Zn}) \) in the coating are required to provide meaningful corrosion protection to the steel
substrate. Also, a minimum GI coating weight of 70 g/m² per side was required to obtain this level of the gamma (Fe₃Zn₈) in the final press-hardened coating. From the large number of corrosion tests and electrochemical measurements that were made, it was shown that the gamma (Fe₃Zn₈) phase passivates and slowly corrodes during representative automotive corrosion tests, whereas the passivation of the α(Fe,Zn) breaks down frequently as corrosion testing proceeds, resulting in significant corrosion before short-term passivation is re-established. Because of the need for gamma (Fe₃Zn₈) phase to provide cathodic protection in the coating, together with the requirement of heating the conventional 22MnB5 direct hot press forming grade to above 782°C to give the required austenization, it was decided to develop two new grades, with 2.0 and 2.5% Mn. Dilatometry work conducted on these two grades showed that it was possible to obtain fully-martensitic structures when they were cooled to temperatures less than 750°C. Cooling rates for the 2.0% Mn steel must be at least 10°C/s, and 5°C/s for the 2.5% Mn steel, to produce fully martensitic microstructures. At McMaster University, significant expansion of this program has been enabled by the NSERC award for the three GAP programs ZCO-53, ZCO-70 and ZCO-79. This has resulted in a combined budget of US$ 921,900 to be provided for the 3-year term, of which the GAP members’ program support of this ZCO-70 program is US$140,625 for the 3-year term. The additional funding has supported construction of a hot press forming simulator that includes both planar and U-channel die quenching. Galvanizing process simulations is allowing assessment of reactive wetting during galvanizing of the 2% and 2.5% Mn grades - already, the 2%Mn grade has been hot dipped in a GI bath using a -30°C dewpoint atmosphere and shown to be adherent after 180° bend testing.

Other investigators have taken different routes to address the problems of liquid metal embrittlement in zinc-coated hot press formed steels while still providing cathodic protection. A thin layer of zinc has been electroplated on to an aluminized sample that has been successfully hot press formed. Also, different alloy coatings, including Zn-Al-Mg, have been investigated for their attractiveness during hot press forming. However, they have lower absolute corrosion potentials compared to pure Zn, making cathodic protection not as effective. Prior to the beginning of 2019, the only Zn-coated hot press formed material available was made by indirect hot stamping with a controlled cooling rate to permit complete solidification of the zinc prior to significant deformation.

IV. PROPOSED PROJECT

The objective of the two-year extension of this project, beyond the NSERC-co-sponsored program, is to examine tailored cooling of the two higher Mn grades developed in this project so that mechanical properties can be varied as a function of location. This will first require that the development of the relationships of mechanical properties to the range of stamping temperatures found useful for these alloys to be developed. In particular, the possibility of forming martensitic and bainitic microstructures in different parts of the hot press formed components will be investigated, using the U-channel die, together with zinc coating of the steels. Because they will be hot press formed below the 782° peritectic temperature, it should be possible to eliminate any risk of liquid-metal-induced cracking during processing of these steels. It may be necessary to construct a larger U-channel die so that zonal cooling can be implemented, unless a suitable die can be used at the location of, or obtained from, project partners.
V. COST AND FUNDING SCHEDULE

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<td>2020-2022</td>
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VI. REFERENCES

ZCO-81 PROGRAM PLAN

“Decarburization Issues in AHSS Processing”

Issued: August 2019

I. OBJECTIVE

The objective of this project is to understand the decarburizing behavior of the main grades of AHSS (dual-phase, TRIP and 3G) during the CGL treatments required for their successful galvanizing, determine the kinetics of the rate-limiting steps found under different conditions and assess the effect of such decarburizing on mechanical properties. The rate-limiting steps are either related to the surface fraction of oxides that block the transport of C from the bulk to the surface, or the steel details that determine the rate of C diffusion through the bulk and near-surface steel volume: the austenite/ferrite phase makeup, grain size and texture, steel composition and possibility of making carbides that could tie up diffusing carbon. Surface coverage by oxides and other constituents that block C diffusion now appears to be the limiting factor, but it is not yet clear that oxides alone limit the rate of decarburization.

II. ECONOMIC INCENTIVE

To be compliant with USA 2025 fuel economy regulations, a 7% mass reduction passenger vehicle mass is required. Similar requirements also apply to other developed nations. The implementation of AHSS in North American body in white and closure applications has exceeded forecasts, growing from 11% in 2013 to 17% in 2018. At the same time, ultra-high strength steel (UHSS, 1GPa strength and higher) has grown from 3% to 5%. It is forecast that by 2027 AHSS and UHSS will grow to 22% and 28% of these applications, respectively. The processing of these steels is expected to include steps where an understanding of decarburization behavior and effects on user properties will be required.

III. BACKGROUND AND CURRENT STATUS

To prevent surface selective oxidation during galvanizing furnace pretreatment, before Zn dipping, advanced high strength steels are increasingly subjected to an oxidation step prior to a reduction step that permits galvanizable surfaces to be presented to the galvanizing bath. Because the diffusion coefficient of oxygen from the surface into the bulk of many AHSS compositions is much higher than solute elements such as Mn, Si, Cr and others that cannot be reduced if they reach the surface of the steel sheet, it is possible to immobilize a sufficient fraction of these elements in an internally-oxidized layer so that only a small portion reach the steel surface, permitting the steel surface to be richer in Fe, which can be easily reduced from its oxidation states to a metallic state that can then be reacted with the galvanizing bath to produce acceptable-quality coatings. Several pretreatment routes are used: either a constant atmosphere,
with a relatively high dew point during the entire pretreatment process; an oxidation stage during preheating, using either a direct-fired furnace or a relatively high dew point gas in a radiant heated preheating section, or an oxidizing zone after preheating but before entering the reducing zone that is normally carried out during soaking. The high dew point is produced by water injection, both in radiant tube (RTF) and direct fired (DFF) furnaces, even if the DFF is run with an oxidizing flame. This controls the partial pressure ratio pH₂O/pH₂ that is manifest as the dew point. The H₂O vapor can be absorbed onto active sites on the steel surface and react with carbon to produce carbon monoxide and hydrogen gas according to the formula:

\[ C + H₂O \rightarrow CO + H₂ \]  

This consumption of water vapor and production of hydrogen results in a lowering of the local dew point. Both a high dewpoint and a sufficient concentration (partial pressure) of water vapor are required so that H₂O diffusion of the boundary layer is not the rate-limiting step, especially at customary H₂ compositions in the furnace gas, i.e. 5%. In any furnace, even with a dew point as low as -50°C, there is sufficient water vapor in the furnace gas so that its supply to the surface of the steel substrate is not the rate-limiting step.

Therefore, the rate-limiting steps will be either related to the surface fraction of oxides that block the transport of C from the bulk to the surface, and steel details that determine the rate of C diffusion through the bulk and near-surface steel volume: the austenite/ferrite phase makeup, grain size and texture, steel composition and possibility of making carbides that could tie up diffusing carbon. Surface coverage by oxides and other constituents that block carbon diffusion now appears to be the limiting factor, it is not yet clear that oxides alone limit the rate of decarburization. If decarburization sufficiently depletes C from the austenite, then it will transform into ferrite in which carbon diffusion is much faster. Moreover, a reduction in the amount of austenite at the soaking temperature near the surface reduces the quantities of martensite or bainite that can be produced upon cooling, affecting local mechanical properties in comparison to the bulk. There will also be an evolution of internal and external oxide development as the decarburizing process proceeds. These phenomena will be influenced by the details of CGL processing and will ultimately determine the characteristics of the galvanized steel.

In addition to steel-related effects, the CO generated as a result of decarburization can result in soot formation in downstream furnace zone and carburizing of the refractory steels used in the radiant tubes in these zones.

Much of our knowledge about decarburization behavior in sheet steels comes from processing electrical steels. Traditionally, decarburization of electrical steels was done by combusting methane, producing an N₂-H₂-H₂O-CO-CO₂ mixture. More recently, this has changed to...
treatment in an N$_2$-H$_2$-H$_2$O mixture and temperatures between 600 and 1000°C, similar to that used for CGL pretreatment$^6$ which has been found to be more rapid than the traditional process. Most electrical steels have a very low C content, meaning that higher processing temperatures are required to reach the austenitic range. Grabke$^7$ studied the decarburization of austenite and ferrite in H$_2$O/H$_2$ mixtures and found that decarburization proceeded according to reaction (1) above. The decarburization reaction producing methane:

$$C + 2H2 \rightarrow CH4$$ (2)

can be neglected for pH$_2$O/pH$_2 > 0.01$. He found that the kinetics of decarburization is governed by the supply and diffusion of water vapor in the gas phase. For steels of interest to CGL processing at very low carbon contents, Henrian activity behavior can be assumed, which then limits the surface reaction because of the very low quantities of C available. There is little, if any activity data for C in ferrite at higher C contents, or in austenite that is stable at still higher C contents at processing temperatures of interest. The model of Dubois includes CO because it fixes the C activity in HNX.$^5$ The prevailing equilibrium in the decarburizing process requires equal C activities in the gas boundary layer with its partial pressure of H$_2$O and the steel surface, with its details of steel and oxide coverage and composition. It was also found that Reaction (1) is very fast as compared with carburization and decarburization CH$_4$-H$_2$ or CO-CO$_2$ mixtures. Therefore, it may be attractive to examine the use of these mixtures in furnace gas rather than H$_2$N$_2$ mixtures to minimize decarburization in higher-carbon steels. These gas mixtures will bring their own issues, such as safety and the sooting phenomenon described above. This work was extended by Soenen$^6$, who examined the balance between the surface reaction and diffusion control of the decarburization process. For commercial thicknesses and industrially-applied dew points similar to the CGL, decarburization was found to be diffusion controlled.$^6$ For low sheet thicknesses and low dewpoints, decarburization is surface reaction controlled. Marra, et al,$^8$ confirmed Grabke’s assumption that the partial pressure of water vapor can be assumed to be constant in industrial furnaces and therefore its concentration in practical terms does not change the decarburization treatment. However, this is an approximation because of the use of steam injection in vertical decarburization furnaces that regulates natural convection (descent of colder gas in the vertical furnaces). The reversibility of the decarburization reaction was also confirmed. Reaction rates decreased when the CO vapor pressure in the vicinity of the steel strip was increased, slowing the reaction rate. The presence of iron oxide buildup on the steel surface also slows the carburization rate. For carbon concentrations typical of advanced high strength steels, decarburization rates are influenced by the phase makeup of the steel. If it is ferritic, carbon was found to be uniformly distributed inside the sheet, but if austenite is present, with its lower diffusion coefficient, the decarburization process is slowed, and a strong carbon gradient is formed.$^9$ Therefore, the furnace atmosphere should be controlled to accelerate the reactions in the austenite range and also avoid excessive oxidation. The effect of Si-containing oxides, such as Fe$_2$SiO$_4$/SiO$_2$ on decarburization rates was studied. The thickness of these oxides was found
to increase with dew point for the electrical steels. Internal oxidation intensity was found to increase with increasing dew point. When $\text{pH}_2\text{O}/\text{pH}_2$ increased to 0.48, a continuous silicon-rich layer was found in the internal oxidation zone, greatly slowing the rate of decarburization.$^{10}$

More recently, decarburization in advanced high strength steels under continuous galvanizing line conditions has been described.$^{5,11}$ In preoxidation tests at CRM it was found that the decarburized thickness maybe as high as 60µm, but the samples used were much smoother than industrial sheet. Higher dew points resulted in higher rates of decarburization. For the CQ steel composition, the oxide formed on the surface did not present a significant barrier to decarburization. For the AHSS grade, C content down to a depth of 2 µm became sufficiently low to transform austenite into ferrite after soaking. During overageing, the developed model predicted that the C content in the ferrite and austenite close to the surface can increase by diffusion from the bulk; however, at the low overageing temperature of 450°C the ferrite formed during decarburization may not transform back to austenite. Microhardness and microstructural measurements would need to be taken to confirm this behavior. Also, the martensite start temperature for many 3G steels is near this overageing temperature which can also influence the distribution of C. For the AHSS, the stronger decarburizing was coincident with less surface selective oxidation of Mn-Si, indicating that the internally-oxidized layer formed during CGL processing was insufficient to block the flow of carbon out of the steel. By contrast, a greater degree of surface selective oxidation was coincident with less decarburization; however, this also coincided with a presumed higher-fraction coverage of oxides on the surface of the steel by the solute elements. In these oxidation/reduction treatments in AHSS with relatively high Si content, hematite was found to be the dominant surface oxide rather than the less compact wuestite that was found on the CQ steel. When soaking was made at 850°C with the AHSS grade, coating adhesion was always found to be acceptable, using the oxidation reduction process, even with 1% hydrogen in the reducing gas. Under this condition, carbon participated in iron oxide reduction at the surface, at the expense of a more severe carburization of the near-surface volume.

IV. PROPOSED PROJECT

Two principal tasks must be undertaken to better understand the rate-limiting steps that are hypothesized to control decarburization during CGL processing. These tasks can be conducted in various CGL furnace zones including DFF (direct-fired furnace), DFI (direct flame impingement) and the following heating, soaking and cooling zones where oxidation/reduction reactions are of interest:

1. Effect of CGL Process Variables on Decarburization Profiles in Selected Steel Grades
   This task will undertake coordinated experimental and thermodynamic/kinetic modelling work to develop and understanding of how steel, microstructural and oxidation
characteristics influence decarburization behavior. Steel grades for which higher dewpoint (e.g. +10°C) dewpoints are required to achieve acceptable coating quality will be subjected to relevant temperatures and soaking times in a galvanizing process simulator. The most important material variable will be C content (C>0.15%, 0.2% preferred). A simple carbon steel with 0.1<C<0.15%, corresponding to a 350 MPa grade, will first be run as a reference. The reference steel will be run with a matrix of 3 dew points and 2 soaking times at a customary fully austenitic soaking temperature to give a baseline for comparison. The candidate steels could include dual phase, TRIP and 3G steels. Two dewpoints, high and low (perhaps -30 and 0°C) will be selected that are expected to give different surface oxide coverage with these compositions, together with different quantities of internally-oxidized layers. Microstructures produced with the CGL process routes will be compared with samples received in an as-cold rolled behavior. Of particular interest will be the nature of surface oxides that are hypothesized to regulate decarburization; one key correlation will be the extent of surface oxide coverage and carbon gradients measured below the steel surface. Processing conditions will be selected where diffusion is expected to be mainly through austenite, and also where a significant portion of ferrite is present (heating and cooling zones, also intercritical annealing soaking zones).

2. **Effect of Furnace CO Profile on Steel Decarburization Behavior**

A simulated typical multi-zone furnace will be simulated for experiments in which the CO profile very near to the moving strip surface can be measured; this is expected to be on the order of the mass transfer boundary layer thickness. Furnace gas velocities, strip velocities, temperature and furnace dewpoint will be varied; it may not be necessary to use a steel strip as the CO source if its rate of emission of C that would participate in Reaction 1 above can be determined in Task 1; other methods could be used to simulate Reaction 1. The condition at the point of measurement will be assumed to be isothermal to simplify modelling, although later modelling work in Task 3 could integrate over temperature histories to describe both decarburization and oxidation behaviors. This task is expected to define C/CO conditions in the mass transfer boundary layer which can then be coupled the Task 3 description.

3. **Development of models of reaction kinetics, diffusion behavior and phase relations**

The experimental and modeling work of Tasks 1 and 2 would be integrated to extend their findings of work and allow prediction of other conditions, ie for other steel compositions and processing conditions. The objective is to develop the ability to predict the C profile for selected grades and conditions by the time the steel reaches the galvanizing bath.

4. **Effect of various decarburization conditions on the steel properties**

Samples of steel grades of interest will be prepared with different amounts of decarburization (and consequently, different microstructural details) as a result of processing according to the conditions found in Tasks 1 and 2. Decarburization depths
exceeding 50 µm were observed in past work. This is expected to particularly effect local elongation performance, for example hole expansion and edge cracking limitations. Both uncoated and coated samples will be tested. It will be necessary to discern between coating, interface and decarburization effects on deformation and fracture.

V. COST AND FUNDING SCHEDULE:

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VI. REFERENCES

2. C. Wagner, Z. Elektrochem, 63 (1959) 772-782.

ZCO-82 PROGRAM PLAN

“Improving Zinc Coating Adhesion”

Issued August 2019

I. OBJECTIVE

The objective of this project is to extend our knowledge of wettability and steel oxidation effects to an understanding of factors affecting Zn coating adherence to high strength steels with the aim of improving this adherence. Normally, a well-wetted Zn coating on a sheet steel substrate is assumed to also be well-adherent. However, with high strength steels, many instances have been observed where there is perfect Zn coating coverage on the substrate, but where poor coating adherence is observed. This project will mainly focus on GI (free Zn overlay) coatings, but also include some effort on ZnAlMg coating compositions used in automotive applications.

II. ECONOMIC INCENTIVE

By the year 2025, 50% of the average total mass of the steel body-in-white and closures in a North American light vehicle is expected to comprise UHSS and AHSS grades, weighing 260 kg. This trend is similar in Europe, Japan and Korea. A better understanding of the relationship of adherence to wettability and other aspects of coated steel behavior is required to improve performance during processes requiring formability and also in-use performance including strengths of adhesive-bonded joints that must perform well during crash testing.

III. BACKGROUND AND CURRENT STATUS

Robust and complete coating adherence is becoming more of an issue with the increased use of adhesive bonding in automobile bodies and structures, either as a supplement to welding and brazing techniques, or as a bonding technique on its own. Coating adherence can be related to both the adhesive force of the Zn coating to the steel substrate, involving one or more intermetallic layers and other features at the interface, or it can be related to limitations of strength below the steel surface; i.e., in areas of internal oxidation. The latter has been studied extensively in the past. Also, wetting phenomena involving Zn on advanced high strength steels has been studied extensively in the past.

It is usual galvanizing line production practice to assess zinc coating adhesion at the delivery end of the line. Tests used by galvanizing line quality control personnel include bending, roll forming, cup and ball impact tests, with the ball being driven into the test material at different speeds. In Europe, it is common practice to use the dynamic ball impact test, described in SEP 1931. However, such coating adhesion tests do not accurately describe the behavior of adhesive bonded zinc-coated steel joints under automotive fatigue and crash loadings. Until recently, the time required for adhesion curing was too long to allow the use of an adhesive-peel test as part of
on-line quality control. However, a recent development has allowed for the use of a one-component adhesive to be used with an elevated curing temperature, permitting samples for adherence testing to be ready for use 6 minutes after delivery of the material from the galvanizing line. In this test, a stud consisting of a flat steel plate joined to a steel cylinder in the normal direction is adhesively bonded to the coated steel. A calibrated energy is then delivered to it from an impact tester. The fracture patterns produced are then assessed to determine if Zn coating adhesion is satisfactory or not.

Much of our knowledge of the nature of coating adherence derives from wettability behavior. It is generally assumed that a well-wetted coating produces a well-adherent zinc coating layer. Many researchers are in agreement that good adhesion of a zinc coating to a steel substrate depends on full development of the Fe$_2$Al$_5$ interface layer. However, use of a hot-melt rotator device, in which liquid zinc is removed from the substrate after wettability by spinning, indicates that the Fe$_2$Al$_5$ layer in many cases is capable of bridging over oxide islands or granules on the steel surface. Therefore, these granules must be considered as part of the overall mechanical couple between the zinc coating and the steel substrate.

In the referenced work, Fe-Si substrates with Si between 0.25 and 3% were studied together with Fe-Mn alloys with Mn between 0.5 and 3%. The wetting dynamics were shown to not only relate to the overall oxide coverage of the surface but also to the size of the oxide islands or granules. As with most wettability studies, measurements of coating adherence were not performed. Wettability studies in which the progression of wetting force or wetting angle with reaction time was observed and related to the progress of interfacial reactions have been carried out by several investigators. The Wilhelmy plate method was used to distinguish between dynamic wetting force measurements during the dipping phase, and static force measurements as the interface layer grew between liquid zinc and steel substrate. The dynamic force did not vary between samples of similar size; however, there were significant differences in static wetting force progression, depending on growth of intermetallic phases. Although coating adherence was not measured, it was noted that the quantities of intermetallic phases produced would produce significant technical challenges.

Wetting angle progressions with time, and the influence of steel surface features, have been also been studied using sessile and glissile drop techniques. Use of a wetting balance with IF and 2.5%Mn DP steels showed a U-shaped dependence on wetting force on dewpoint with the DP steels: at the lowest dewpoint, where fewer oxides were present, the absolute value of the wetting force was low, also at high dewpoints where internal oxidation also lowered the presence of surface oxides this wetting force was also low. The influence of relative velocity of liquid Zn to steel surface during dipping was observed in a galvanizing simulator in which zinc bath flow was induced. Reynolds numbers of 8,000 at 460°C were produced, changing the nature of flow of zinc along the strip from laminar to turbulent. This induced flow was found to greatly improve wettability, as evidenced by the decreased number of bare spots. Bend tests were also used to determine the effects of zinc flow along the strip on adhesion failure. Surprisingly, increased flow increased adhesion failure, which was explained by the higher amount of residual selective
oxidation, which reduces sites favorable for production of the Fe$_2$Al$_5$ inhibition layer. Chemical composition was found to be unchanged, regardless of whether stirred or unstirred baths were used.\textsuperscript{13}

The effects of high dew point furnace pretreatment on zinc wettability and adherence on dual-phase and TRIP steels was studied in GAP Project ZCO-54.\textsuperscript{14} In this study, although perfectly-wetted Zn coatings could be produced, internally-oxidized layers at a depth of 5-20 µm under the steel surface resulted in the least resistant portion of the coated steel as it was bent. It was possible to find the surface side of the steel substrate on the delaminated zinc coating produced during bending tests, meaning that failure had progressed through the internally-oxidized layer.

Manipulation of steel chemistry has also been investigated to improve wettability in coating adherence. The substitution of a part of the Si in a Si-Al alloyed steel with Al, together with high dew point processing, resulted in improved wettability and adherence. Because of the increased formation of aluminum oxide at the steel surface, which suppressed the coexistence of (Si, Mn) oxides, the ability of the Al oxide to coexist with the Fe-Al-Zn inhibition layer formed in the GI bath was also seen as beneficial.\textsuperscript{6} Details of the interfacial reaction between solid Fe and liquid Zn in Fe-0.1% Si and Fe-1% Si steels were carried out where the Fe-Si phase is in equilibrium with the zeta phase and liquid zinc. Limited solubility of Si in the zeta phase enriches Si between the zeta phase and the steel substrate, prolonging the time when the liquid zinc phase is present at the interphase layer. These experiments were made with Al-free zinc baths, meaning they are relevant to either general galvanizing, or instances in continuous galvanizing where sufficient soluble Al has been consumed by other reactions to put the equilibrium into the phase regime where Zn-Fe rather than Zn-Al-Fe phases are stable.\textsuperscript{15} The effect of a 1.0% Cr addition on coatability behavior of a 1.5% Mn steel showed that the wetting contact angle decreased from 130 to 105° as the Cr addition increased up to 0.6%. However, when the Cr addition increased from 0.6 to 1%, the contact angle increased back to 130°. The decrease in contact angle for the lower compositions was related to the reduction of the MnO and Cr-Mn spinel by soluble aluminum. The spinel is thought to react with Al more easily than MnO because Cr is less oxidizible than Mn. It is possible for Al to react with the Cr-Mn spinel to form a ternary spinel of Cr-Al and Mn. The decrease of wetting angle at higher Cr concentrations is believed to be related to an increase in Cr selective surface oxidation.\textsuperscript{16} The addition of Ni and Cu to advanced high strength steels to improve coatability in alloying behavior was first investigated by Takata.\textsuperscript{17} They demonstrated that the amount of Si and Mn oxide formed under reduced Fe decreases, in these cases, changing the oxide morphology from film-like to spherical. This was followed by similar studies investigating the effects of V on the Fe-Al interface reaction of Galvalume with low-carbon steel sheet.\textsuperscript{18} The influence of Bi on selective surface oxidation of a 590 TRIP steel with 1.5% Si was investigated, using Bi additions to the steel chemistry of 0-0.19%. Thick Mn-rich and thin Si-rich oxide layers were formed on the Bi-free steel, whereas lens-shaped oxides were formed on the surface of the Bi-added steels.
Bi was found to segregate to the surface by grain boundary diffusion, where it decreased the oxygen concentration of the subsurface, suppressing internal oxidation. This resulted in improvement of galvanizability with the production of a continuous and dense layer of fine Fe$_2$Al$_3$ interface crystals; however, adherence testing was not conducted.\(^1\)\(^9\) The influence of Sn additions in the range 0.005-1\% on the oxidation behavior of a 1.5\% Mn-1.5\% Si TRIP steel was investigated, giving the same transition behavior as seen with the Bi-added steel described above. On the 0.05\% Sn-added steel, the morphology of the Si-rich oxide layers changed from film-like to lens-shaped, whereas the Mn-rich oxides remained granular. At 0.5\% Sn, only lens-shaped oxides islands were formed. On the 1\% Sn-added steel, lens-shaped oxide islands and film-type Si-rich oxide layers were formed. All of the Sn-added steels produced well-wetted coatings.\(^1\)\(^9\) Similar effects have been observed for Sb\(^2\)\(^0\) and Cu.\(^1\)\(^7\)\(^,\)\(^2\)\(^0\)

Pre-plating of metallic surfaces compatible with continuous galvanizing line processing has also been investigated as a way of improving wettability. These include Fe,\(^2\)\(^2\)\(^,\)\(^2\)\(^3\) Cu\(^2\)\(^4\) and Ni.\(^2\)\(^5\)\(^,\)\(^2\)\(^6\) Ni was found to affect the nucleation rate of the different intermetallic phases formed at the interface of the coating in steel, including NiAl$_3$ and also NiZn delta and gamma phases. Use of Ni as an addition to the bath with Al, to form an Ni-Fe intermetallic, has been explored. To influence coating interface structure, the production of brittle intermetallics was noted in Reference 26; however, no adherence testing was performed in any of these investigations.

Beyond gas treatment of steel surfaces to influence oxidation behavior, use of a surface treatment technique involving lithium boron oxides has been described.\(^2\)\(^7\) This liquid salt bath is operated between 650 to 800\°C and was successful in coating a Si TRIP steel, together with a Mn-TWIP steel. Samples showed good coating adhesion after a 1.5 T-bend test.

Other mechanical characterizations of zinc coatings that involved characterization of coating adherence include tensile testing\(^2\)\(^8\) and measurements of work of adhesion, which relate more to wettability behavior than mechanical adherence, which is the focus of the proposed project.\(^2\)\(^9\)

Recent work in our ZCO-75 wettability program at CRM has used a 2.6 at\% Al / 2.9 at\% Mg bath composition. Wettability and coating quality were found to be significantly affected by the Al/Mg oxide covering the bath surface. If steel wetting is poor, this oxide will stick on the panels when they are removed from the bath. The Al/Mg oxide particles on the bath surface affect coating appearance much more severely when bath wetting of the steel substrate is poor, because in this case the floating oxides are attracted by the strip. On the contrary, in the case of a well-wetted, these floating oxides are repulsed from steel surface.\(^3\)\(^0\)
IV. PROPOSED PROJECT

Several tasks are proposed to improve our understanding of the nature of zinc coating adherence on high strength steels:

1. Effect of galvanizing bath saturation on interface layer development. Many advanced high strength steels with high Mn and Si contents at the present time are run in campaigns on galvanizing lines that otherwise run lower alloyed grades. It is suspected that many of these baths are not fully saturated in Si and Mn, which can influence the nature of their reactivity and interface layer development. In Reference 10, zinc baths were intentionally over-saturated with Si and Mn, to give levels of 0.17% Al-0.003% Si, and also 0.16% Al-0.8% Mn, together with 0.18% Al and 2.6% Mn. These were expected to improve the wetting reaction by enhanced formation of Fe-Zn intermetallics; however, coating adherence measurements were not carried out on the produced samples. A designed experiment, in which levels of Al, Si and Mn were varied to determine their effect on interface layer development, together with subsequent wettability and coating adhesion performance, could be conducted for a range of IF, DP and TRIP steels.

2. Effect of surface active elements on coating adhesion. As described above, the effects of Sn, Sb and Cu have been found to change surface oxide morphology and therefore permit good wetting behavior. The investigation of these additives and their effects of coating adhesion could be included in a broader examination of the effects of oxide bridging behavior of the Zn coating that is known to allow for good wettability for many steels. The portion of the steel that is oxidized and the portion that is unoxidized (wetted by the liquid zinc directly to produce intermetallic compounds) is considered in the modified Cassie equation where the wetting behavior is determined by the relative composition (i.e., surface coverage) of the oxide and metal phase. This approach was combined with modification of the Avrami growth law develop a new description of the dynamic Cassie equation. This could be applied to different steel grades with well-characterized oxide/reduced metal surfaces to determine not only their effect on wettability, but also on subsequent adherence behavior.

3. The development of interfaces other than Fe$_2$Al$_3$ has been investigated for wettability and morphology effects, but never for coating adherence. It is possible to conceive of intermetallic layers such as Fe-Si, Fe-Ni and others produced during the wettability and galvanizing reactions that have the potential to provide satisfactory adherence during relevant formability and adherence tests. The approach to developing such interfaces could use both bulk steel and precoating techniques.
4. The above three tasks will be adapted for a study of ZnAlMg coatings, depending on the results obtained in the investigation of GI coatings. Solubilities of several elements, notably Fe, and other effects of composition-related chemical equilibrium, including the role of oxides, are expected to require adaptation for studying the behavior of ZnAlMg automotive coatings.

V. **COST AND FUNDING SCHEDULE:**

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<td><strong>GAP Program</strong></td>
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VI. **REFERENCES**


I. OBJECTIVE

The objective of this continuing project is to gain further understanding of the relationships between surface properties of advanced high strength steels that affect emissivity, including roughness characteristics, the nature of oxide distribution on the surface of these steels as they are prepared for hot dip galvanizing and other factors, such as composition that may also influence emissivity. Also, to relate the deviations in temperature caused by these changes in emissivity to deviations in mechanical properties of these steels.

II. ECONOMIC INCENTIVE

The ability to control variations of AHSS mechanical properties within specifications, together with maintaining of coating quality details (including GI, GA and Mg-containing coatings) is very important for the economic performance of the galvanizing line. If this cannot be achieved, then the amount of non-prime material produced is excessive and lower income is realized. Surface-specific details, and variations in these details, of the hot rolled or cold rolled strip entering the galvanizing line influence process outcomes in complex ways and are difficult to isolate from each other. Preoxidation prior to annealing sections of the furnace influences roughness, which may not only be mechanically created but also be a consequence of reduction steps after initial oxidation steps in the galvanizing pretreatment furnace and therefore not always measurable from the outside surface. Recent findings in this project indicate that roughness exists on different scales (micrometer and tens of nanometers) and cannot always be correlated with mechanical roughness measurements; they are sometimes best measured by electromagnetic means and strongly influence emissivity. The results of this project will help provide guidance to galvanizing line operators to increase their production of prime material.

III. BACKGROUND AND CURRENT STATUS

Advanced high strength steels processed in continuous galvanizing lines are much more sensitive than lower-strength grades to variabilities in temperature during the thermal cycles used to prepare strip for dipping in the galvanizing bath. Much of this variability is caused by variations in emissivity of the strip surface. This variation makes accurate temperature measurement by the usual pyrometry technique very difficult, resulting in low or high actual strip temperatures versus the pyrometer being used to control the furnace, even when dual wave length pyrometers are being used.\(^1\) Strip condition variabilities that affect emissivity include the oxidation condition on the strip surface; strip roughness characteristics\(^2\); the strip microstructural condition and how it evolves during the heat treatment cycle; the presence of any surface defects, especially larger-scale artifacts such as near-surface voids and flaps; and variations in strip thickness and shape.
(camber and waviness) in both transverse and longitudinal directions that affect thermal mass and the actual cross-section exposed to radiation heat transfer. Our work to date in this project has also shown that it is the fine-scale roughness that has the greatest influence on emissivity at the wavelengths important for pyrometry; longer wave length roughnesses and other artifacts do not significantly contribute to this emissivity property, this correlates with other recent industrial work.

Since this program began in 2014, it has been the recipient of two supplemental funding awards from National Science and Engineering Research Council of Canada (NSERC). The first, to Ecole Polytechnique de Montreal, doubled our initial program budget from $150,000 for the three-year period to $300,000. It involved only IZA and ArcelorMittal Dofasco as project partners. The second grant, to University of Waterloo, with additional support to Ecole Polytechnique de Montreal and McMaster University, provided $219,160 US support that added to contributions from IZA, Stelco, Williamson, SRB Controls (the Canadian subsidiary of Williamson) and Teck Metals, to give a total program effort of US $355,000. This has allowed development of experimental apparatus at University of Waterloo, including a thermal simulator utilizing a controlled protective atmosphere in which two spectrometers are mounted covering the wavelength range of interest, together with an industrial pyrometer provided in kind by Williamson. The FTIR (Fourier Transform Infrared) Spectrometer is a particularly valuable instrument purchased for this project, capable of measuring emissivity as a function of wavelength over the important 1.25-16.6 μm wavelength range. The usefulness of any relationships between optical reflectivity and conventional RMS roughness appears to be limited. Work to date has found that the roughnesses affecting emissivity properties are mainly related to features on the microscale that include oxide nodules which can change emissivity as they form and grow, and other chemical and morphological changes that may perturb electromagnetic waves (at the wave lengths used for pyrometry) as they couple with ions and electrons within the metal and oxide. Therefore, the surface of the steel being measured dynamically changes as it is taken through the simulated galvanizing pre-treatment process, meaning that local emissivity, and therefore the relationship between luminescence and temperature, changes as the strip moves through the furnace zones. A fractal approach was taken to examine the surface of dual-phase steels after various thermal treatments relevant for the galvanizing process. Filtering of wave lengths, to examine only smaller wave length details, appears to be a promising way to reconcile physical roughness with the roughnesses obtained from electromagnetic theory. These optical roughness features are now being analyzed and interpreted by use of the Kirchoff-Helmholtz diffraction theory. The nature of changes in oxide and other features on the surface affect surface topology and need to be well related to this this theory to provide a formal framework for understanding the effects of these features on emissivity. The Ecole Polytechnique de Montreal work is measuring and interpreting the effects of thermal excursions that would be expected to be caused by inaccuracies in pyrometry on mechanical properties for the steels being examined. Results from the first stage of this project were presented at Galvatech 2017. Additional steel chemistries from partners are expected to be received as the expanded program develops.
IV. PROPOSED PROJECT

Research currently being conducted in this project on how surface details of AHSS influence spectral emissivity, and how these features evolve during continuous galvanizing process steps, will support the primary objective: developing an understanding of how these details influence pyrometric temperature measurement. This knowledge should enable new pyrometry algorithms to be developed, using a Bayesian analytical approach. Much of the effort in the foreseen 2020-2022 project will be directed towards meeting this objective. The second objective, determining how temperature deviations affect the mechanical properties and zinc layer adhesion of the galvanized AHSS samples will be conducted at Ecole Polytechnique de Montreal, using galvanizing simulation equipment at McMaster University. Both the current DP steels being examined in this project, together with those donated by other GAP members, will allow for development of a generalization of how the consequences of inaccuracies in measuring emissivity affect mechanical properties and adhesion of the zinc layer.

V. COST AND FUNDING SCHEDULE

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<td>Surface Profile Effects on AHSS Processing</td>
<td>2020-2022 GAP Program</td>
<td>$55,000 per year for 3 years ($165,000)</td>
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VI. REFERENCES


3. K. Lin, S. Trivett, K.J. Daun, “Impact of roughness length scale on spectral emissivity during intercritical annealing of advanced high strength steels,” Materials Science and Technology (MS&T) Conference 2018, October 14-18, Columbus OH.


ZCO-83 PROGRAM PLAN

“Coating Weight Stabilization”

Issued August 2019

I. OBJECTIVE

The objective of this project is to combine a refined version of the multi-slot McMaster air knife design, which greatly stabilizes near-strip gas flow, and one or more of the available strip position stabilizing techniques that allow strip-to-knife distance to be more precisely held. This should allow closer strip-to-knife distances to be maintained in the wiping rig, increasing wiping power and also greatly increasing the efficiency of N₂ wiping, with minimal dilution by O₂, for coating control knives operated in this manner. To support the work on ZnAlMg coatings, a task on liquid alloy properties determination is included.

II. ECONOMIC INCENTIVE

This project addresses several issues that are among the most sensitive cost items for galvanizing line operations. The improvement of accuracy of coating control will have an important effect on the overall cost of the galvanizing operation. At present, most lines operate with an average aim coating weight 18% above the guarantee. For a 2-side coating weight of 270 g/m² this results in an excess Zn utilization of 48 g/m². For a 1 mm thick sheet this results in 6 kg/ton of excess Zn. At a price of $1 per pound this adds more than $13/ton to the cost of production. Galvanizing costs are also limited by available line speeds, especially with thinner gauge product using thinner coatings. The problem is expected to become more critical as thinner alloyed coatings become more common. The present industrial best practice for a GI coating is 120-130 meters per minute for a 5 µm coating, 160-165 meters per minute for a 7.5 µm coating and 190-195 meters for a 10 µm coating. Although some lines have been designed for speeds in excess of 200 m/min., no results of coating weight practice have been reported above this speed.

III. BACKGROUND AND CURRENT STATUS

The need to provide accurate, uniform and reproducible coating thickness control continues to be one of the major challenges for the successful and economical operation of a continuous hot dip galvanizing line. Reduction of Zn coating mass to a reliable specified minimum, especially with alloy coatings, continues to be a goal of most galvanizing line operators and these lines must be operated at increasingly high speeds. Our existing program at McMaster University is approaching the conclusion of its 5-task approach to improving reproducibility and stability of gas jet coating control equipment as summarized below. While the focus on this program has been upon improving stability of the gas wiping jet that influence wiping power and coating
uniformity, strip stability is also a key factor in ensuring wiping success. Several approaches to improving strip stability can be considered: electromagnetic stabilization, using devices now available industrially from several suppliers, or new technology developed by CRM that shows great promise in improving stability of the “foot” of the strip, as it emerges from the Zn bath.

McMaster University has recently concluded the program co-funded by NSERC (National Science and Engineering Research Council of Canada) and GAP program sponsors.²

**Task 1.** Design and testing of single- and multi-slot air knives. Operating curves were developed and confirmed for relevant ranges of jet gap widths, strip-to-knife thicknesses and plenum pressure, showing conditions where production is expected to be the most robust.

**Task 2.** Parametric study of single- and multi-slot knives. This task developed accurate measurements of shear stress near the strip surface to improve accuracy of the wiping model for these two knife designs. The oil interferometry technique was developed and implemented and used to measure wall shear stresses for both laminar and oscillating jets. The results were scaled to high Mach number jets.

**Task 3.** Developed a pilot scale wiping apparatus to confirm the validity of the Task 2 analytic model. The effect of jet configuration (single-slot versus multi-slot) on coating thickness reduction was measured.

**Task 4.** Full-scale testing at the facility of industrial partner ArcelorMittal Dofasco gave valuable information on the performance of an actual single-slot knife that informed other tasks in the program.

**Task 5.** Fundamental understanding of unsteady flow effects on coating quality and noise generation. The multi-jet air knife was shown to significantly reduce self-excited oscillation associated with high velocity single jets. The results were modeled using proper orthogonal decomposition and were found to be related to aeroacoustic feedback. A significant reduction in jet oscillation was found to be possible using the auxiliary jets, although the overall mechanism is not yet clear.

Electromagnetic strip stabilization is accomplished by sensing of the strip position across its width as it emerges from the gas wiping rig and regulating an electromagnetic force delivered by magnetic coils. The stabilization can be placed as close as 25 cm above the wiping rig.³ In one example the strip-to-knife distance was reduced to 6 mm, bringing the strip within the outer range of the jet core. Blower pressure was also reduced from 310 to 222 mb (4.3 to 3.2 psi).⁴ Shape correction, over a limited range, can also be effected, such as crossbow.⁵

At CRM, a hydrodynamic device has been developed and patented to improve strip stability, and also strip shape, at the exit from the galvanizing bath.⁶ The liquid Zn entrained into the contained volume above the bath is directed to form hydrodynamic “pads” on either side of the strip. The hydrodynamic force can be controlled to obtain a flat, stable strip when it reaches the wiping knife vertical position. Results have shown that strong damping of strip resonance is possible, and also improvements in strip shape. There is a minimum critical speed to obtain the
hydrodynamic effect, which is typically in the range of 60-80 m/min. Yet to be investigated are the effects of the hydrodynamic device on coating roughness and waviness.

For either stabilization approach, the multi-slot McMaster design is expected to contribute to stability because it should now be possible to operate the wiping knives in a way such that the jet core impinges on the strip at the wiping position \((Z/D=4\) where \(Z=\)strip-to-knife distance and \(D=\)knife outlet slot dimension\). As already shown industrially, a lower gas pressure would also be possible with low \(Z/D\) operation, making it possible to rely less upon the auxiliary jets less for jet stabilization.

When using \(N_2\) as the wiping gas, significant dilution by entrained ambient air is known to occur when \(Z/D\) values are large, which is when higher gas pressures are required.\(^7\) As the strip-to-knife distance is decreased, it may be possible to reduce the knife gap but this will also reduce gas flow. Dubois\(^7\) has calculated that \(Z/D\) is still the key parameter, meaning that for a defined distance the \(O_2\) concentration at the sheet will be higher for thin-slot gaps; however, gas flow will be lower.

IV. PROPOSED PROJECT

1. Fundamentals of Liquid Zinc Alloy Properties

A review of the known physical properties of relevant zinc alloys for sheet galvanizing has found several important gaps. Whereas the density, surface energy and viscosity of nearly pure zinc compositions and casting alloys have been known for many years, they have not been investigated for the range of ZnAlMg alloys of interest, other than by extrapolating existing models from known properties. A laboratory task will measure and determine these values, together with precise measurements of density, over the range of industrially relevant temperatures.

2. Scale-Up Trials with Multi-Slot Knifes and Strip Stabilization

A cooperative trial will be undertaken with one or more interested GAP members. To minimize equipment and operating expense, it is proposed that a relatively narrow strip width be used. The strip must be of sufficient width to permit full development of gas flow patterns expected with wider strip. A line utilizing one of the strip stabilization techniques described above will permit for low \(Z/D\) positioning of the optimized McMaster gas knife design, with the goal of running close enough so that the jet potential core impacts the wiping zone. The knives will be designed so that both single-slot and multi-slot operation are possible, making it possible to judge the benefits of either design.

The galvanizing line will be operated over a range of line speeds and coating weights of interest. Coating waviness and roughness will be determined for both GI and Zn-Al-Mg coating types. Several other variables, such as strip shape (edge drop) and use of baffles can be considered.

The objective of this work will be to determine if it is possible to consistently operate in the region where the jet core is impinging on the coated strip to cause the wiping action. The
benefits of the apparatus for nitrogen wiping will also be determined, as determined from waviness and roughness measurements.


During the production trials held with the above experimental plan, dross measurements will also be taken, for both nitrogen and air operation. The effect of the stabilization device and the knife designs on dross production will be determined by comparing measurements on this line with those from other lines, by scaling (m²/h of coated steel vs dross production and other scalable measurements).

V. COST AND FUNDING SCHEDULE:

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<td>GAP Program</td>
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VI. REFERENCES

2. ZCO-56, “Improving Coating Weight Consistency,” Final Progress Report, McMaster University, Issued March 2017 and subsequent reports at GAP Program Review Meetings.

I. OBJECTIVE

Galvanizing bath pot rolls are usually grooved to ensure that the roll turning torque is able to overcome bearing friction and inertial forces and therefore minimize roll skidding. However, because the surface inside the roll groove is not contacted by the steel strip, it is subject to dross buildup phenomena similar to that observed on other non-contacted surfaces of the roll, for example, on the work roll surfaces outside of the strip width. The objective of this project is to take a detailed look at the roll groove environment, extending the tools that we have already developed for computational fluid hydrodynamics to develop insights into the nature of dross buildup in roll grooves, for both coated and uncoated rolls, and suggest ways of minimizing or even eliminating roll groove buildup.

II. ECONOMIC INCENTIVE

The service life of galvanizing bath hardware submerged in the hot dip coating pot continues to be a major limitation on the productivity of all galvanizing lines. Two factors affect this lifetime: the durability of the bearings used to support rotating hardware and dross buildup on hardware surfaces that can interfere with the passing of strip through the zinc bath. It has been determined that the annual cost for line downtime for North American galvanizing lines is around $800,000 per year. If this is a representative figure, then the cost of this downtime worldwide is $480,000,000, for the 600 hot dip galvanizing lines known to exist in 62 countries.

III. BACKGROUND AND CURRENT STATUS

Although the thermal environment in the roll groove can be assumed to be similar to other portions of the moving pot roll surface, there are several important differences between the roll groove environment and the other non-contacted surfaces on the roll: first, the nature of fluid flow is cyclic, with the roll groove exposed to the galvanizing bath in the non-wrapped portions of the roll circumference, and being constricted by the presence of the strip in the wrapped portions of the circumference. The nature of fluid flow at the transition between wrapped and unwrapped areas has never been studied in detail but is likely to include areas of high-turbulence velocity with almost no boundary layer, with respect to either fluid flow or composition details. Second, by the time the strip contacts the wrapped area of the roll, it can be expected to have formed an interface layer, either Fe2Al5 for GI coatings or at least a zeta layer for production of GA coatings. The nature of the fluid flow at the point of contact between the strip and roll can be expected to influence either the growth of these interface intermetallic compounds if they
remain adherent, or to dislodge them, potentially into the roll groove volume, if forces are strong enough to make them non-adherent. It is very likely that the interface there re-grows during its subsequent time of immersion into galvanizing bath. This interruption of interfacial growth, in comparison with the portions of the strip surface that are in full contact with the surface, is believed to be one of the causes of roll groove marks have been observed in many instances.

Preliminary work investigating roll groove phenomena was carried out in multi-phase flow modeling at University of Western Ontario, concluding in mid-2015. This work showed that shallow and wide grooves allowed for full penetration of liquid zinc flow into the volume of the groove and gave better behavior than deeper, narrower grooves. The characterization of sink roll groove marks had been included in the ZCO-57 project, a task carried out by Teck Metals. The presence of dross in the grooves could clearly be seen. In some cases, these were associated with zeta outbursts. The use of sink roll coatings to minimize sink roll groove buildup was also investigated by Dewey, et al. The use of a sealer over the tungsten carbide-cobalt roll coating that permitted good performance to be obtained. Our current ZCO-57 project at Metals Centre Leoben/University of Leoben has determined that it is the vertical component of the zinc flow velocity near the roll contact surface that has the greatest influence on rate of dross growth. This component increases as the roughness of the built-up layer increases. The relative magnitude of this vertical velocity component may be greater in the roll groove in comparison to the roll contact surface, when the strip is not contacting the roll, and may be much higher at the points where the strip contacts and releases from the roll.

Computer modelling work with square shape groove geometries of 2 x 2mm pitch 22mm, 4 x 4mm pitch 44mm and 4 x 5.5mm pitch 44mm by Dubois suggested that the fluid pressure at the point of strip-to-roll contact is greater than the point where the strip departs from the roll, so that there should be a flow of zinc through the groove in the angular direction, in the same direction as roll rotation. The high pressure at the strip contact point should reduce the change of dross pickup on the roll surface in this area, and there should be an increase in dross pickup at the point of strip departure because of the low pressure condition. Results were sensitive to groove design and line speed.

Our past GAP programs on corrosion of bath hardware in galvanizing baths provide information on the performance of several kinds of alloys and coatings in GI and GA baths. These include 316L stainless, the Fe-based superalloy MSA2020, 410 stainless steel, 1015 carbon steel and the intermetallic compounds Fe₃Al and FeCrSi.

IV. PROPOSED PROJECT

After review of past work, including conditions that had been used in past simulations and experiments, a computational fluid hydrodynamics model will be developed, based on our past
capabilities. Three regions are of interest: the unwrapped portion of the roll in which the roll surface is exposed to the free flow of the galvanizing bath, where boundary layer effects, dross attachment and other effects, are likely to be important, the points of contact and departure between the strip and the roll, where significant expulsion or induction of liquid metal has been observed to occur, and the wrapped area of the roll circumference where there is a confined volume of liquid metal and reaction products from both the strip and the bath contained in the volume. The model is expected to answer the following questions:

1. In steady state, isothermal operation with uncomplicated conditions, can the model simulate observed dross buildup in the roll groove?

2. What is the effect of strip entry temperature and line speed on dross roll buildup?

3. What is the effect of roughness in the roll groove on dross buildup in the groove? This can also consider previous dross buildup as a contributor to surface roughness. What is the effect of roll groove geometry (micro versus larger size grooves)

4. What is the effect of changing surface energies (roll coatings and sealers) on groove buildup?

5. How do surface features in the galvanized coating, where sink roll groove defects are observed, correlate with sink roll buildup? Can a laboratory simulation, in which deformation is imposed on the in a steel strip to simulate its wrapping around the roll with a severity that causes deformation into the roll, inform us about the nature of defects that may occur from the situation?

6. How do expected conditions at the point of initial contact between the strip and roll, where it begins to be wrapped, influence conditions on both the strip surface and the groove surface? Do the imposed forces have the capability of removing or compromising the intermetallic layer that has just been formed on the steel surface? Does it have the capability of removing built up dross that is already present in the roll groove, ejecting it into the bath volume (and possibly attaching it to other locations of the sink roll groove surface)?

Validation of the computer model, and supply of required data, will be required from laboratory experiments. These will include deformation experiments simulating the deformation that is expected to occur with a thin, low-strength steel passing around the roll under high line tension, producing sink roll groove marks and resulting influences on the intermetallic layer, also the use of rapid fluid flow to determine if it is possible to remove the intermetallic layer at the point of initial contact between strip and roll by a surface shear mechanism that will depend on surface
roughness. Beyond these laboratory experiments, field data from project sponsors will also be essential, including samples of materials exhibiting sink roll groove marks and photographs, together with sections of failed rolls, to investigate the nature of reactions occurring in the sink roll groove.

V. COST AND FUNDING SCHEDULE:

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<td>ZCO-84</td>
<td>Dross Buildup In Pot Roll Grooves</td>
<td>2020-2022 GAP Program</td>
<td>$50,000 per year for 3 years ($150,000)</td>
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</table>

VI. REFERENCES


6. ZCO-57 Project Presentation, GAP Program Review Meetings, May 2019


57


ZCO-85 PROGRAM PLAN

“Kinetics, Growth & Dissolution of Galvanizing Drosses”

Issued August 2019

I. OBJECTIVE

To develop experimental data that address the most important shortcomings in our understanding of the mechanisms of nucleation and dross growth and dissolution, for both bottom and top drosses, in galvanizing baths. These mechanisms are related to the kinetic coefficients relating to the nature of growth, the curvature of the local surface, together with the microscopic composition, temperature and flow conditions surrounding the dross particle in the local volume of the galvanizing bath.

II. ECONOMIC INCENTIVE

Between 8 and 9 grams of dross are produced for every square meter of sheet steel that is galvanized. Considering only sheet galvanizing production of 25 MT in the EU27 in 2015, if the average sheet surface area is 200 m²/T then an average of 42.5 kT dross wastes were generated in 2015. By itself this a significant economic loss, but this dross is also responsible for unscheduled galvanizing line stops described in the ZCO-84 Economic Incentive and downgrading of product quality.

III. BACKGROUND AND CURRENT STATUS

Hot dip galvanizing is inevitably accompanied by formation of dross because of the continuous introduction of steel into the galvanizing bath. Here, “dross” refers to iron-containing compounds formed with constituents of the galvanizing bath caused by conditions exceeding the solubility of these elements at a given temperature in the galvanizing bath. Dross cannot be completely avoided, even if best practices are observed; however, significant steps have been taken to understand how it can be minimized.

The velocity of growth of a dross particle growing from precipitation is given by the following formula:

\[ V_n C_1 (1 - k_0) = D_s \frac{\partial C_s}{\partial n} - D_l \frac{\partial C_l}{\partial n} \]

Where \( V \) is the velocity of growth, \( C_1 \) and \( C_s \) are concentrations of the liquid and solid, respectively, \( k_0 \) is the partitioning coefficient, \( D_s \) is the diffusion coefficient of solute in the precipitated solid, and \( n \) is the near-field distance. \( C_s \) is assumed to be constant within the dross, and diffusion inside the dross is very slow; therefore, the first term on the right-hand side can be
dropped. The remaining right-hand term describes diffusion in the liquid, which is controlled by local hydrodynamics. The initial composition the liquid is described by the following formula:

\[
C_i' = C_0 + \frac{1}{m_i} \left[ \left( T_{eq} - T_0 + \Gamma \kappa \cdot f(\varphi, \theta) \right) \cdot \frac{V_n}{K} \right].
\]

Where \( C_0 \) is the initial composition of the galvanizing bath at that location, \( m_i \) is the slope of the liquidus line, \( T_{eq} \) is the equilibrium temperature, \( T_0 \) is the initial temperature, \( \Gamma \) is a coefficient, \( \kappa \) is the curvature and \( K \) is the kinetic coefficient.\(^9\)

The concentration gradient of solute in the surrounding liquid is influenced by the local velocity. This was simulated in our ZCO-8-10 bath management Project at National Research Council of Canada (NRC) by using a stirrer in the bath with rotational speeds between 200 and 500 rpm. It has also been simulated in our ZCO-57 program at University of Leoben by imposing different conditions on the boundary layer next to a moving pot roll. The kinetic coefficient \( K \) is much greater than 1 (unity) for dendritic growth and very small for faceted crystals. In the case of dross precipitation, the preferred direction of growth of zeta (\( \text{FeZn}_{13} \)) phase is very well known, so that faceting effects are quite strong, giving a very low kinetic coefficient. In contrast, \( \text{Fe}_2\text{Al}_5 \) growth is less constrained by faceting. The curvature term is very orientation-dependent. In all the models developed to date, dross particles are assumed to be cubic. In our ZCO-57 project, cubic constrained growth was assumed by tessellation of a cubic field, where growth only occurred from the corners of each cube.

Dross size effects are also important. Until now, a constant Gibbs-Thomson coefficient has been assumed as crystals grow. Small dross particles are in equilibrium with the surrounding liquid at lower temperatures than larger crystals. This has implications for both precipitation of new particles and dissolution of larger particles and may explain some of the difference in kinetics between dissolution and growth that we have observed in the ZCO-8-10 project, especially the slow dissolution of larger particles. This effect is related to changes in the bulk free energy caused by the curvature of the interface surface under tension. To obtain a full understanding of this size effect, it may be necessary to measure the wetting angle of the galvanizing bath liquid with each of the dross compounds. Consistent with this, the ZCO-8-10 dross precipitation and growth results for zeta phase were more consistent at 500 RPM, but not at 200 RPM.\(^{10}\) However, these kinetics were an improvement over previous galvanizing line sampling analyses where dross particles were assumed to “dissolve instantly” as conditions changed from super-saturation to under-saturation.\(^{11}\)

The first reported experiments on dross behavior were made by Barnhurst.\(^{12}\) In these experiments, only GI baths were used, with the main objective being to relate galvanizing bath
conditions to inhibition layer thickness. Together with metallographic examination of coated samples, the Barnhurst work developed relationships between average dross particle sizes as bath composition was changed from 0.12 to 0.2% Al and back and also increasing or decreasing bath temperatures between 480 and 450°C. No attempt was made to further characterize dross particle sizes and shapes. S. Yamaguchi developed kinetic rate constants between all phases of interest in the galvanizing bath using electrochemical techniques. In all cases, heterogeneous nucleation was assumed. This work was most useful in determining the kinetics of dross transformations between GI and GA operations; for example, Fe$_2$Al$_5$ to delta (FeZn$_7$) phase, zeta to delta phase and gamma-one (Fe$_5$Zn$_{21}$) to delta phase, and reverse. No analysis of dross particle size or analysis was given.13 Arioka14 performed detailed dross precipitation and growth experiments in unstirred GI and GA baths. Detailed dross growth measurements were made. The observed data were used to develop an Ostwald ripening relationship where growth is controlled by the diffusion of solute, where the solute was both dissolved Al or Fe. No agglomeration was considered. Also, the Al and Fe solubilities were assumed to remain constant with time, the dross particles were assumed to have an equilibrium shape, each type of dross particle had a defined size distribution as growth proceeded and the cube of the mean particle radius was in proportion to the holding time. These assumptions made it possible to develop relationships for zeta, delta, gamma-one and Fe$_2$Al$_5$ dross particles which were assumed to be monoclinic, plate-like hexagonal, face-centered cubic and orthorhombic with 14 plate faces, respectively. Each dross particle was observed to have certain habit planes and grew while keeping stable planes, confirming the nature of faceted growth. No distinction was made between homogeneous and heterogeneous nucleation.

Work on an industrial hot dip galvanizing line by Mallens, et al.15 used galvanizing bath sensors to obtain a rough estimate of the kinetics of dross formation and dissolution in a GI bath. Their bath model used the derived formation and dissolution rates for top and bottom dross from industrial observations instead of equilibrium compositions. The amount of dross $Y_{dross}$ formed or dissolved after a certain amount of time was described using the first order of Avrami equation:

$$Y_{dross}(t) = (1 - e^{-Kt}) Y_{dross}^e(t)$$

where $Y^e$ is equilibrium value for the new amount of dross formed after the new bath state is reached based on the ternary phase diagram. The DEAL software allows calculation of equilibrium amounts of top and bottom dross. The rate constant K depends upon the temperature via the Arrhenius equation and is expected to be different for each reaction. Rate constants between 3.16*10$^{-4}$ and 5.6*10$^{-7}$ per second were found for the various reactions that transform one intermetallic to another, considering the zeta-to-delta, zeta-to-gamma-one, delta-to-gamma-one and reverse, gamma-one-to-Fe$_2$Al$_5$ and delta-to-Fe$_2$Al$_5$ reactions. The reaction rates for the
latter two are relatively fast. The direct transformation of zeta to \( \text{Fe}_2\text{Al}_5 \) is not predicted by the equilibrium phase diagram and was not measured.

Like the Mallens work, our work in the ZCO-8-10 Program used a LIBS (laser-induced breakdown spectroscopy) sensor to conduct a systematic experimental laboratory study on the effects of temperature variations and mixing rates on the formation and dissolution of dross particles.\(^{16}\) The results of the LIBS analysis determined the effect different levels of dissolved Al and Fe in the bath. Metallographic cross-sections determined the volume fraction, and also the mean size and shape of the dross particles were measured. Temperature was changed between 500 and 435°C for Al compositions in the GI and GA range. The composition of the bath was also changed from 0 to 0.18% Al at a constant temperature of 460°C by the addition of Zn-5%Al brightener bar. It was found to be difficult to quantify particle growth as a function of the parameters used in this study at either the 500 or 200 RPM stirring rates. Part of this may be related to the relatively small size (20 kg) of the zinc bath, which could not serve as a reservoir for dissolved Al and Fe to the extent possible with a larger bath, relative to the quantities of Al and Fe participating in the growth/dissolution reactions. Consistent with this, higher stirring rates resulted in larger particles in all cases. As expected, the 0.08% Al bath only produced zeta particles that were highly faceted. At 0.12% Al, both delta and also an Al-containing delta phase were found. At 0.15% Al, the \( \text{Fe}_2\text{Al}_5 \) compound was found. The isothermal test, in which composition was varied, showed that in the transition from zeta to delta to \( \text{Fe}_2\text{Al}_5 \), particles were produced that had different compositions in the solution, confirming industrial observations. Therefore, the use of the simple taxonomy of gamma, delta, zeta and \( \text{Fe}_2\text{Al}_5 \) is actually more complicated, with significant Al found in Al-containing delta phase, and significant zinc contained in the \( \text{Fe}_2\text{Al}_5 \) compounds. Although this is well known from observations, the range of stability of these more complicated particles, and their role in dross precipitation and growth paths occurring as conditions in the galvanizing bath are changed, has not been given much attention.

### IV. PROPOSED PROJECT

It is proposed to conduct a series of laboratory dross precipitation and growth experiments using the general approach of Arioka\(^{14}\) augmented with the techniques developed for our GAP ZCO-8-10 Project.\(^{16}\) Careful experiments and good experimental design should be able to help us address the following questions, with the use of a LIBS analysis, different rates of bath stirring and the Arioka technique.

1. Can the kinetics of both heterogeneous and homogeneous nucleation in GI and GA baths be characterized, as temperature is changed?
2. Is it possible to relate dross growth or precipitation rates to particle size (Gibbs-Thomson kinetics)?
3. Can the crystal shapes described by Arioka be confirmed (monoclinic, hexagonal plate face centered cubic and orthorhombic geometries)? How does the aspect ratio or sphericity of these particles change with time? These data are needed to refine the “cubic growth model” that has been used to simulate growth for all dross types until now, per project ZCO-57.

4. What is the role of agglomeration in dross particle growth? Do agglomerated crystals have different dissolution rates than single crystals?

5. How do growth rates change as the composition gradient surrounding the dross particle changes? This relates to important issues with regard to dross particles near moving pot hardware, inductors and the moving steel strip. Such information is needed to further validate any future analysis of dross growth on moving bath hardware and similar components.

6. Is it possible to measure the wettability of typical galvanizing bath compositions on dross particle surfaces? For this, it is likely that bulk intermetallics will need to be grown and used in wetting experiments with liquid galvanizing baths, similar to the wettability experiments described in the ZCO-82 Project proposal document.

Although the work described here is very fundamental in nature, it is of great practical consequence if we are to further advance in our knowledge of dross management and minimization, especially in areas where dross presence is critical, such as in the snout, near the moving strip and bath hardware components and at the exit from the bath, together with areas where less zinc movement is seen, such as the stagnant areas that are present in several characteristic portions of the galvanizing bath.

V. COST AND FUNDING SCHEDULE:

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<td>Kinetics, Growth &amp; Dissolution of</td>
<td>2020-2022</td>
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<td>Galvanizing Drosses</td>
<td>GAP Program</td>
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VI. REFERENCES

1. N. Setargew and D. Yuen, “Top dross formation in metal coating baths”, Galvatech 2013, pp. 455-462
ZCO-78 PROGRAM PLAN

“Influence of Substrate Oxides, Texture and Microstructure on Quality of Galvanneal Surface Appearance”

Issued August 2019

I. OBJECTIVE

The nature of formation of the galvanneal coating, by interdiffusion with the steel substrate, means that prior processing steps can strongly affect appearance, especially for exposed quality coatings. Such substrate-related factors include the completeness of scale removal after both slabbing and hot rolling steps, commonly performed by water jet removal and pickling, respectively, and the crystallographic textures controlled by both hot rolling and cold rolling steps. The details of these steps can also influence near-surface chemical composition and formation of oxides that further influence the growth of the galvanneal coating. The objective of this program is to continue linking together these effects so that identified defects in the galvanneal coating have a sound scientific basis for remediation.

II. ECONOMIC INCENTIVE

Surface appearance issues with coated automotive products can result in downgrading from prime full-finish quality to unexpected or even general-purpose quality, with a significant effect on sales price. An understanding of these issues will contribute to less loss of prime quality galvannealed sheet.

III. BACKGROUND AND CURRENT STATUS

Since this program began in 2017, four sets of study samples have been from GAP members. Three of these included samples in the galvannealed condition, all provided full hard cold rolled uncoated conditions and one provided as-rolled hot band and also pickled conditions. One sample of galvanized (GI) was also investigated. Cross-section and surface plane observations were made on the microstructural level using light stereomicroscopy and scanning electron microscopy. Detailed microstructural characterization was carried out using a time-of-flight secondary ion mass spectrometer (TOF-SIMS). This has enabled determination of surface defects details. Related to these defects, modeling has allowed for prediction of surface oxides that could be present on the surface of the steels with their indicated compositions, and these have been related to the microstructural observations. Defects were related to pot roll groove details, the presence of interface oxides that influenced GA coating formation and growth, and the correlation of red scale defects on the hot band with defect locations. The GI surface defects appeared to be related to splashing that occurred in the coating control area.  

1.
IV. PROPOSED PROJECT

During the continuation of the project, a tighter focus will be given to the origins of appearance differences in the galvanneal samples that have been received. Characterization will be made of the substrate portions under localized portions of the coatings having different appearances. These are expected to include the nature of substrate textures, the oxidation states that are present in the alloying elements within the steels and the distribution of these oxides at and near the steel surface and within the GA coatings, the nature of reactivity of the steels and coatings and the nature of the GA coatings themselves. Additional samples from GAP sponsors will be required to allow for a more complete analysis required for meeting program objectives.

V. COST AND FUNDING SCHEDULE:

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<td>Influence of Substrate Oxides, Texture and Microstructure on Quality of Galvanneal Surface Appearance</td>
<td>2020-2022 GAP Program</td>
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VI. REFERENCES

ZCO-80 PROGRAM PLAN

“Zinc Effects on Mechanical Behavior of AHSS Welds”

Issued August 2019

I. OBJECTIVE

To further investigate some of the important gaps in our knowledge related to solving the important LME (liquid metal embrittlement) problem: an underlying key cause is stress-assisted zinc diffusion into steel grain boundaries. The role of specific starting microstructures on LME sensitivity, the origin of several particular crack geometries that are important for LME, and better understanding the influence of coating type on LME sensitivity, together with an extension of our work on evaluating mechanical performance of these spot welds, including cross tension shear testing are all included in 2020-2022 program objectives.

II. ECONOMIC INCENTIVE

One of the major advantages of steel-based automotive manufacturing is the ability to join together the steel sheet components of the automotive structure rapidly and at low cost using fusion welding techniques, including resistance spot welding and laser welding. Aluminum-based manufacturing typically uses in mechanical joining, such as clinching, together with adhesive bonding, that are higher-cost and slower processes than steel fusion welding processes. To allow these steel joining processes to continue to be used as efficiently as possible, it is necessary to understand the nature of embrittlement by zinc from the galvanized coatings that has been occasionally observed in welds in the steel grades that are expected to enable continued lightweighting of steel-based vehicles.

III. BACKGROUND AND CURRENT STATUS

Use of higher-strength steels, particularly those with high austenite content (greater than 5%), has led to observations of liquid metal embrittlement (LME) that occur when resistance spot welding zinc-coated steels with these and higher austenite contents.¹-⁴

Our current project at University of Waterloo has been multiplied in effort by award of a grant from National Science and Engineering Research Council of Canada (NSERC) of $300,000 US. This adds to the $135,000 US of cash support provided by the GAP Program. The industrial partner that is supplying in-kind support is ArcelorMittal Dofasco. This project is using several dual phase and TRIP steels with retained austenite contents between 0 and 16%, with a range of coating conditions: uncoated, GI or GA-coated. The project has confirmed past results that cracking is more severe and more frequent with higher heat input in high-austenite materials and that increasing external loading increases LME crack severity. Even low-susceptibility materials can develop large cracks and create interfacial cracking in the weld nugget under high enough
loading. This is especially seen with imposed weld misalignment. A study in the current project of grain misorientation angles in the base metal near zones of zinc penetration showed that zinc penetration only occurs along high-angle grain boundaries and that twinning boundaries also play a major role in zinc penetration. All observations indicate that LME cracks initiate from the coating/steel interface and then propagate intergranularly along prior austenite high-angle grain boundaries within the upper critical heat-affected zone. The work has also identified a “ductility trough” where liquid metal embrittlement is observed to start after reaching a temperature of 650°C, and not appearing at temperatures above 900°C. This correlates with results of other work. Location of cracks also appear to be related to their severity, with the most severe imposed stresses occurring in cracks lying perpendicular to the direction of imposed stress. A lower imposed force is always observed to result in cracking of coated steels versus uncoated steels. A cracking index has been defined according to the formula:

\[
\text{Crack index} = \frac{\text{no. of cracks} \times \text{lognormal mean crack length}}{\text{sheet thickness}}
\]

Where: number of cracks accounts for the probability that a crack will be found in a critical location, lognormal crack length determines whether the crack is of sufficient length to cause a loss in strength and the sheet thickness relates to the critical crack length through strength loss. Finite element analysis has been carried out to model the resistance spot welding process. This is giving insights into the stress and temperature fields occurring during resistance spot welding with the various material and process variables investigated in this project.

Three ways of reducing the severity of LME (lowering the value of the Crack Index) have shown promise in the current project:

1. Use of multi-pulse and pre-pulse welding, which reduce LME cracking by diffusing iron into the zinc coating. A balance between alloying and excess heat input can be determined.
2. Use of a ramp down current which reduces the Crack Index especially in the center region of the nugget (Type A). This investigation also showed that the formation mechanism of Type A cracks is fundamentally different than Type B (shoulder) cracks
3. Use of a low-radius electrode geometry, rather than truncated cone or dome geometries, greatly reduced the development of Type B cracks. The stresses caused by electrode shape were found to be primarily thermally driven, rather than caused by mechanical stress. This could relax electrode alignment requirements.

Work has also been initiated on investigating the effect of coating type on susceptibility to liquid metal embrittlement.

A wide and rich literature has emerged during the past few years on LME of zinc-coated advanced high-strength steels. These include a comprehensive review paper on the subject, work from this project on liquid metal embrittlement during laser welding of 22MnB5 zinc-
coated steels, and publications on zinc-coated TRIP and quench and partition steels, which have appreciable amounts of retained austenite.\textsuperscript{5-12}

IV. PROPOSED PROJECT

1. Evaluation of the specific role of starting microstructures and alloying elements on LME sensitivity, especially how they affect the nature of stress-assisted zinc diffusion along grain boundaries. To date, our project has focused on available commercial steels having typical microstructures. The role of alloying elements, especially Mn and Si, on LME sensitivity, has not been systematically evaluated. These alloying elements and their oxides are expected to influence the metallurgical equilibrium occurring in these steels, their reactivity with the zinc coating during manufacture and spot welding and electrical resistivity.

2. There are four types of cracks that occur in LME of zinc-coated resistance spot-welded steels:

   Type 1: Periphery cracks, close to the edge of sheet/electrode indentation;

   Type 2: Cracks of similar length to Type 1 cracks but extending into the nugget from the weld periphery (shoulder);

   Type 3: Short, isolated cracks located only in the nugget region of the weld;

   Type 4: cracks originating from the notch of sheets drawing together at the faying interface extending inward toward the nugget.

Of these, Type 2 and Type 3 cracks have received the least attention; however, it is known that both types of cracks generally form during weld expulsion, and during expulsion the weld periphery, together with the nugget volume, become susceptible to LME crack formation. This work would investigate the thermo-mechanical pattern of nugget crack formation, to see whether small cracks indeed originate in the nugget, while peripheral cracks originate from outside the nugget volume and then propagate toward the nugget.

3. Effect of coating type on LME sensitivity. This work has begun to investigate reduction of LME severity by diluting the GI coating with a layer of aluminum. This raises the boiling point of the liquid coating when it is initially melted and mixed together with the zinc coating and from our project results appears to lower the severity of LME. The use of other coatings, including Zn-Al-Mg coatings that have the potential of modifying the boiling point of zinc, will also be investigated to determine their ability to lessen LME severity.
V. COST AND FUNDING SCHEDULE:

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<td>“Zinc Effects on Mechanical Behavior of AHSS Welds”</td>
<td>2020-2022 GAP Program</td>
<td>$50,000 per year for 3 years ($150,000)</td>
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VI. REFERENCES


ZCO-86 PROGRAM PLAN

“Zinc Alloy Coatings Microstructure and Coating Thickness Effects on Performance”
Issued August 2019

I. OBJECTIVE

To produce and evaluate coatings with a range of microstructural features expected in industrial production, together with a range of coating thicknesses that are either presently or possibly could be used in the future, to determine the influences of microstructural features and coating thickness on performance of Zn-Al and Zn-Al-Mg alloy coatings, focusing on automotive performance.

II. ECONOMIC INCENTIVE

Thin alloyed coatings have grown in use in automotive applications during the last 6 years. Incentives for use include processing advantages in forming and welding, required for most automotive body assembly operations, with improvement in corrosion resistance. Thinner coatings should show less variability in surface appearance than thicker coatings, all other conditions being equal. In multi-material automotive structures, it is reported that ZnAlMg coated steels perform better in comparison to GI coated steels in combinations with other materials like PHS-AlSi as well as aluminum.1

III. BACKGROUND AND CURRENT STATUS

For coatings containing less than 5% Al, the largest microstructural feature, also occupying the largest volume fraction, is the zinc dendrite or primary crystal. In Zn-Al alloys, this is surrounded by the binary Zn-Al eutectic. In Zn-Al-Mg alloys, coatings containing less than 5% Zn have the same primary zinc phase; the secondary phases are a binary eutectic consisting of lamellae of smaller zinc crystals and MgZn2 and a ternary eutectic, consisting of a mixture of a smaller volume of MgZn2, Zn and Al phases in distinct formations. Although the Mg2-Zn11 phase is occasionally found, cooling rates in industrial production are too rapid for it to be regularly observed.2

The effect of microstructural coarseness of the ZAM (3% Al-2% Mg) composition on corrosion performance was studied by Prosek.3,4 He produced coarser microstructures by heat treating at 340°C for up to 72 hours. Zn-6%Mg and Zn-16%Mg coatings were also included, that were heat treated for up to 72 hours. These were compared with the performance of pure Zn and pure Al. The heat treatment of the Zn-Mg-Al compositions resulted in appearance of the Mg2-Zn11 phase, which was measured at a composition of 6-7% Mg and 1% Al. The coarser microstructures resulted in higher mass loss when these coatings were subjected to the Renault ECC-1 cyclic corrosion test for 24 hours. The same work also exposed Zn-1.5%Al-1.5%Mg coatings produced
with 60, 70, 100, 120, 200, 275 and 350 g/m² two-side coating weights to the SCAB test (outdoor exposure, accelerated by spraying with 5% Na-Cl three times per week). The 60 and 70 g/m² coatings began to show red rusting after 10 weeks of exposure. Significant differences between the Zn-Al-Mg coating thickness corrosion performance was seen after half a year of exposure. These were compared with Zn-0.2%Al coatings with 140 and 160 g/m², which were entirely red rusted after one year of SCAB testing, corresponding to the results seen with the 60 and 70 g/m² Zn-Al-Mg coating. An examination of Zn-Al-Mg coatings with quaternary alloy additions, conducted under the GAP program, showed that corrosion performance of microstructures that had finer phase distributions tended to show improved corrosion performance. In particular, Zn-Al-Mg-Si compositions performed significantly better in both open and confined (hem flange) configurations. This was linked to a lower acceleration of corrosion by local galvanic microcells and limited spatial pH variations. Similar work was conducted by Krieg, et al., who studied binary Zn-Mg with compositions of 1%, 2% and 3% Mg, cooled to give local solidifications times of 1 or 8 minutes. The Mg-Zn₂ intermetallic was also fabricated and its corrosion properties characterized. Increasing Mg content resulted in a finer and more evenly-distributed amount of lamellar eutectic. Coarser microstructures were seen with these slowly-cooled alloys. The first two stages of corrosion (activation and active corrosion) were similar for the coarse and fine microstructures; however, the third stage, formation of a protective layer, increased with microstructural fineness and was related to improved corrosion performance.

The influence of coating composition on the nature of surface oxides was studied for coating compositions in the range of Zn-1.5%Al-1.5%Mg to Zn-3.7%Al-3.0%Mg. In the topmost layer, only a few nanometers thick, the concentration of Al in the surface layer increases with the higher concentrations of Al in the coating. Within the surface layer of the Zn-1.5%Mg-1.5%Al coating, thinner Al-rich oxide areas were preferentially located above primary Zn dendrites, similar to GI coatings. For higher Mg and Al compositions the surface layers showed a high uniformity. Moreover, when measurements for all of the investigated coatings were averaged over extended areas, a similar chemical nature of the oxide layer for all of the investigated coatings was concluded to exist.

Regarding formability, the effects of coefficient of thermal expansion mismatch between the different phases observed in Zn-Al-Mg coatings has been observed to affect deformation behavior. Part of this is related to the anisotropy of Young’s modulus in the Zn primary crystal. Anisotropy effects were mainly observed in Zn-2.5%Al-3%Mg coatings, not in Zn-6%Al-3%Mg coatings where there is a significant amount of isotropic Zn in a face-centered cubic phase, despite the high amount of Zn.

The influence of the presence of the Mg-Zn₂ eutectic has also been related to paint delamination behavior. No cathodic delamination was observed at the paint-MgZn₂ interface; delamination always proceeded by anodic delamination triggered by the migration of ions at the interface. To
reduce this driving force of ions, it was recommended that the potential gradient be reduced, mainly by adjusting the composition of the Mg-Zn oxide found at the surface of the metallic coating. It was speculated that corrosion of painted product could be improved by producing a Mg-containing oxide film at the surface metallic coating and encouraging this by the use of pretreatments.\textsuperscript{10}

The scanning Kelvin probe technique has been well developed to measure galvanic and related electrochemical and homogenies at or near the surface of metallic coatings. This has been applied to Zn-Al-Mg coatings and is described in detail in Reference 11. Finally, the effects of alloying elements on the crystallization kinetics of solidifying zinc, has been described. The results shown are relevant to understanding the effects of cooling rate and alloy composition on the features of polyphase microstructures.\textsuperscript{12}

IV. PROPOSED PROJECT

In this project, only coated steel sheet compositions would be included. These are expected to include industrial samples over the range of interest for automotive applications, generally in the hypoeutectic composition range (less than 5% Zn). The ideal situation would be for industrial production of a range of cooling rates and coating thicknesses with different Zn-Al-Mg coating compositions, perhaps by producing such samples at tails of coils. If this cannot be done, it will be necessary to produce the required samples on a hot dip galvanizing process simulator. Good experience has been achieved with production of Zn-Al-Mg ternary coatings over the range of interest for this project, and the manipulation of coating weights and cooling rates should be possible over ranges of interest.

The produced samples will be characterized by quantitative metallography/image analysis to determine phase makeups, especially the presence and size of the primary Zn, together with binary and ternary eutectic constituents. It is expected that a key factor relating to performance is the relative size of these microstructural features to the overall coating thickness and therefore one index of selection of samples for corrosion performance will be the number of grain diameters that are present across the coating thickness.

Scanning Kelvin probe measurements will be made on both as-received and also on samples after selected corrosion exposures to determine the nature of electrochemical heterogeneity on the surface. To discriminate between differences in corrosion performance with the steady variables, simple accelerated tests, such as salt spray testing, are inappropriate; a cyclic test, perhaps including some periods of outdoor exposure, will need to be selected that is able to discriminate between performance. Corrosion performance will be correlated with scanning Kelvin probe and microstructural and coating thickness observations, including the nature of protective surface films that are formed.
Corrosion performance will also be assessed on deformed samples, likely using a cup test or similar, relevant for automotive applications.

The influence of microstructural features on formability will also be assessed. This is expected to include both T-bend and cup testing. The relationship of coating thickness of GI to performance in these tests is already well known, and it therefore may be possible to limit this testing to coating weights of the greatest interest, varying only the fineness of microstructural features.

The effects of microstructural fineness on automotive paintability will also be assessed. Similar to the formability work, coating thickness of greatest commercial interest will be chosen, with a range of microstructural fineness as the independent variable. These will be subjected to typical automotive pretreatment and primer treatments, using a cyclic test such as the SAEJ2334 or VDA233-102 test. Edge and scribe performance will be assessed and related to the presence of microstructural features where coating delamination is observed.

V. COST AND FUNDING SCHEDULE:

<table>
<thead>
<tr>
<th>Project</th>
<th>Title</th>
<th>Year</th>
<th>Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZCO-86</td>
<td>Zinc Alloy Coatings Microstructure and Coating Thickness Effects on Performance</td>
<td>2020-2022 GAP Program</td>
<td>$60,000 per year for 3 years ($180,000)</td>
</tr>
</tbody>
</table>

VI. REFERENCES


2. K. Honda, W. Yamada and K. Ushioda, “Solidification Structure of the Coating Layer on Hot Dip Zn-11%Al-3%Mg-0.2%Si-coated steel sheet, Mat. Trans v. 49 (6), 2008, 1395-1400, (Japan Institute of Metals).


ZCO-87 PROGRAM PLAN

“Interface and Performance Issues in Non-Fusion Joining of Zinc-Coated Steels”

Issued August 2019

I. OBJECTIVE

To make a broader examination that others have made until now of the principal factors affecting brazing quality of zinc-coated advanced high-strength steels. This will include an examination of the several applicable modes of gas-metal arc (GMA) brazing (short circuit, pulse and other methods) types of filler wire, overall heat balance relating to wire feeding rate and other variables, and the nature of the reaction of the brazed filler metal with the zinc coating and the underlying steel. This is likely to also include the electrical characteristics of the steel in the vicinity of the joints, including the nature of local oxides on or near the interface between the zinc coating and the steel substrate. The reaction of the brazed filler metal, especially Cu-Si, that can create Fe-Cu-Si intermetallics, is also of concern.

II. ECONOMIC INCENTIVE

The use of brazing in body-in-white construction began in the mid-1990’s. Both GMA and laser brazing are used to join body seams during vehicle manufacture, and GMA is also growing rapidly in body repair work, replacing fusion welding for joining of high-strength steels. Although high welding speeds can be achieved with the laser brazing process, its gap bridging ability is poor because of the small diameter of the focused laser beam. The GMA process must be run at lower speed, but the larger area heated by the arc greatly improves gap bridging ability. Process instabilities related to the zinc coating require a broader approach, especially for joining of high-strength steels.

III. BACKGROUND AND CURRENT STATUS

The sensitivity of advanced high strength steels to microstructural and mechanical properties changes occurring during fusion welding has led to the increased use of non-fusion techniques to join various components of automotive bodies and structures. Brazing, using a copper alloy filler metal and the GMA process, has been reduced to practice for automotive assembly for roof rails and other joints where long seams need to be joined. Various issues have arisen during process and product development trials, together with qualification procedures for implementation and manufacturing. Most of these have been solved by a narrowly focused effort to solve the problem at hand. The continued growth and use of advanced high strength steels is making it attractive to consider conversion of other joints that have traditionally been fusion welded, to avoid compromising the developed strengths in the advanced high strength steels, especially those with high levels of martensite. This is seen of special interest for third generation steels, which have high levels of both austenite and martensite: the first constituent is known to be
susceptible to liquid metal embrittlement and the second to tempering in the heat-affected zone surrounding the fusion zone. Gas metal arc brazing of galvannealed IF steels was studied by Makwana, et al., by using the short-circuiting mode of metal transfer during the GMA process, and arcing at low power. They reduced the heat input into the base metal; however, a significant volume of Fe-Si intermetallic compounds were produced as a result of reaction of the Cu-3% Si filler wire with the GA coating and the underlying substrate. Low heat inputs resulted in inadequate wetting of the steel surface, reducing the wetting angle, bead height and spread length that are required to obtain good joint strength. Conversely, high inputs led to excessive spatter of zinc and increase in the intermetallic layer thickness, with higher concentrations of Si in the intermetallic particles at the interface. A narrow process window was achieved for successful brazing that avoided these problems.\textsuperscript{1} This work was later extended to development of a model that estimated the wetting length of a Cu-3%Si deposit on a GA-coated steel; the model considered GMA and laser-brazed joints.\textsuperscript{2} An Auto/Steel Partnership program evaluated the effects of GMA welding and GMA brazing on advanced high strength steels and ultra-high strength steels to determine the effects of welding and brazing variables on joint strength. The GMA welding was conducted on GA and GI coatings over a range of dual-phase, complex phase and bake-hardened steels. A lap joint arrangement was used, with 100-micron-thick shims placed on faying surfaces of the sheet steels. For brazing, a silicon bronze filler wire and a 100% argon shielding gas was used. Process parameters were manipulated to obtain the target braze size. Micro-hardness traces were taken transverse to the weld direction. The focus of the brazing work was only on the BH240 and DP490 steels, with little attention given to the higher strength grades investigated in the welding task, such as DP780, 780SF and DP1180.\textsuperscript{3}

Laser brazing process optimization was reported for a 235 MPa GI coated sheet steel, using a butted flange joint geometry and a Cu-3%Si filler wire. The process was optimized for weld penetration and weld width for this ytterbium fiber laser process.\textsuperscript{4}

IV. PROPOSED PROJECT

It is proposed to extend the narrowly focused past work conducted by others in several broader directions: First, to examine a wider variety of advanced high strength steels than has been examined in the past, notably at higher strength levels with appreciable fractions of martensite and retained austenite in the base metal; to include both galvanized and galvanneal coatings in a wide variety of tests, together with uncoated steel; to examine both short circuit and pulsed GMA processes and their effect on braze quality; to examine both state of the art and developmental filler wire compositions, including Cu-Si, Cu-Al and possibly other compositions; and to examine joint geometries of interest to automotive assembly operations.

Brazed joints produced over this range of materials and process variables will be subject to both mechanical and physical evaluations. These will include tensile testing of both lap and butt joints and examination of the nature of reactions and transformation occurring in the coating and
steel localities that participate in formation of the brazed joint. This will include the adjacent heat-affected zone. A description of the reactions and products produced at the coating/steel interface as brazing proceeds will be developed for each of the brazing processes and variables used. It is expected that results of this project will help advance the capabilities of brazed joints and their contribution to performance of steel-based auto bodies and structures.

V. COST AND FUNDING SCHEDULE:

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