CRACK FORMATION DURING HOT-DIP Zn COATING DEFORMATION

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Abstract

Zn-based alloys are widely used mainly as a protective coating in corrosive environments. Therefore, their research is mainly focused on their corrosion resistance properties and less effort is devoted to the study of mechanical properties, particularly to potential defects under mechanical load in certain applications.

The aim of this paper is to characterize the cracking behaviour of three coatings: Zn, Zn5Al and Zn5Al0.5Mg on a steel substrate before and after plastic deformation. This behaviour has been studied by observation of cracks occurred on the surface and on the longitudinal section after bending in various angles (0°, 5°, 10°, 15°, 30°, 60°, 90° and 180°). Metallographic sections were prepared by conventional metallographic procedures and cracks were observed by laser scanning confocal microscopy (LSCM).

Higher bending angles and more complex chemical composition led to formation of higher number and density of cracks, especially in case of alloy system containing Mg. With higher bending angles cracks transformed from interface, confined and surface cracks to through cracks. However, this type of crack exposes the substrate to the environment. Coatings after plastic deformation showed significantly improved cracking behaviour.

Keywords: Zn-based alloys, crack, plastic deformation

1. INTRODUCTION

Research on fracture mechanics of galvanized coatings is currently limited. Study of microstructure, adhesion of coating layer or coating thickness is very important for final determination of mechanical properties of coatings. Ochiai et al. [1] examined the influence of the coating thickness and applied strain on a crack density of galvannealed coatings under tensile loading. Song et al. [2] experimentally and numerically investigated fracture behaviours of galvanized coatings that contain only the η layer under tensile loading. Furthermore, alloying elements and the corresponding inhibition layers were found to influence the adhesion properties and hence interfacial strength of the coatings [3, 4]. Tzimas and Papadimitriou [5] examined the fracture behaviour of the multiphase layered coatings under 3-point bending of galvanized coatings prepared at 560 °C comprising δ, δ+η, and η phases. They deduced from crack population measurements that the crack density is dependent on the magnitude of applied strain but independent of the coating thickness. Ploypech et al. [6) investigated the influence of the coating layers' thicknesses on fracture resistance of the zinc-iron intermetallic layers of galvanized coatings subjected to four-point bending. The critical bending angle and hence the fracture resistance were found to decrease when either the total intermetallic thickness or the relative intermetallic layers' thickness increases. Enlarging the η layer was found to help slowing crack growth in the intermetallic layers. Above mentioned publications provide deeper understanding of crack formation which is crucial for future development of new coatings and production technology. Present study further extends general understanding by introducing the statistical results of crack formation in hot-dip galvanized coatings prepared via double dip process.

2. EXPERIMENTAL

Wires were coated using traditional continuous hot-dip galvanising process, using the double dip approach and subsequently drawn through a series of drawing dies. High carbon steel was used as a substrate. Nominal chemical composition is provided in **Table 1**. Diameters of the wires are presented in **Table 2**.

Table 1 Nominal chemical composition of used steel (wt.%)

C	Si	Mn	Ni	P	S	Cr	Mo
0.85-0.9	0.15-0.3	0.5-0.6	max 0.1	max 0.02	max 0.02	max 0.08	max 0.02

Table 2 Diameters of investigated wires for cracking resistance measurements

Zn	Zn 1st draw	Zn5Al	Zn5Al 1st draw	Zn5Al0.5Mg	Zn5Al0.5Mg 1st draw
6.0 mm	5.5 mm	6.1 mm	5.5 mm	6.6 mm	6.1 mm

Straightened wire of approximately 0.6 m was cut in 16 cm long sections, convenient for further analysis. For plastic deformation, crack initiation and crack propagation studies a three-point bending (**Figure 1**) was used with 15 mm bending radius. Bended wires were then cut using linear precision saw in a way that the apex region of bends could be mounted in a conductive resin for preparation of longitudinal cross section. Further metallographic preparation consisted of grinding and polishing. Grinding started with 80 grid water resistant sand paper until longitudinal axial cross section of the sample was achieved. Preparation further continued with grinding by 240 and 600 sand papers using water as a coolant. For 1200 and 2500 sand papers alcohol was used as a coolant to prevent the sample from corrosion. For polishing, polishing clothes for nonferrous metals with diamond suspension 3 µm, 1 µm and 0.25 µm were used. At least three crack types and crack density measurements were performed on each coating of each bend and average value was reported.

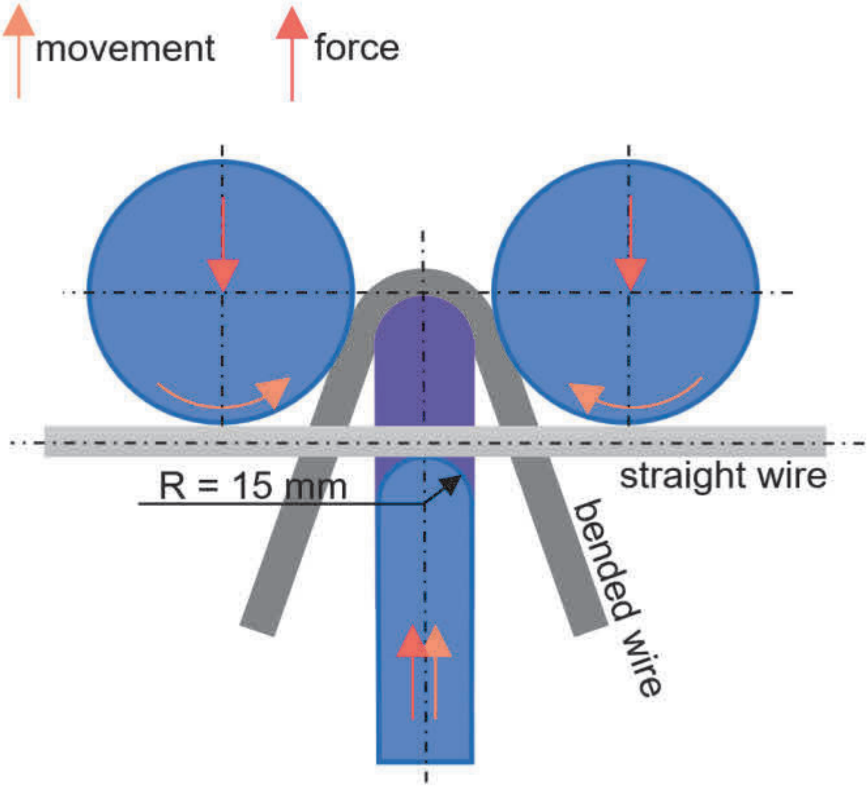

Figure 1 Three-point bending illustration

Crack types and crack density were studied on laser scanning confocal microscope ZEISS LSM 700 in bright field mode. Measurement of crack density was inspired by Tzimas and Papadimitriou [5] who defined crack density as a quantity of various types of cracks in dependence on distance from the apex of the bend. Distance was set to be 10 mm, 5 mm on each side from the apex of the bend. This distance was divided into 10 sections, each 1 mm long. Number of cracks was determined for each section and separated according to their types. Final evaluations resulted in the series of graphs for each coating and bending angle.

To evaluate the results with proper satisfaction, one has to be aware of imperfections and limitations the study is inevitably affected with, such as: coating microstructure variation around the circumference as well as along the wire length, wire diameter and coating weights differences. Furthermore, cracks are observed on the plane which represents the central plane in longitudinal direction and passes through the apex of the bend. Not every crack, however, appears to form on this plane. Instead, cracks may form on both sides of the wire off the central plane. These cracks can reach the central plane and will influence the final identification of crack types. For example, a through crack localized right next to central plane can be identified as a confined crack on the central plane.

3. RESULTS& DISCUSSION

According to Ploypech et al. [7] the crack type distribution was analysed resulting in a dependence of the bending angle-on-crack type. Since three morphologically (chemically) different types of coatings were analysed, crack type differentiation was modified, in contrast to Ploypech et al., to provide satisfactory comparison between the coatings. Cracks were divided to four classes (colour variations are used for a differentiation in the graphs, **Figure 2** is presented as an example): Interface - initiates at the substrate-coating interface and doesn't reach the surface, Confined - confined crack in the coating, doesn't reach surface nor substrate, Through - crack which exposes the substrate, Surface - initiates at the surface of the coating and doesn't reach the substrate.

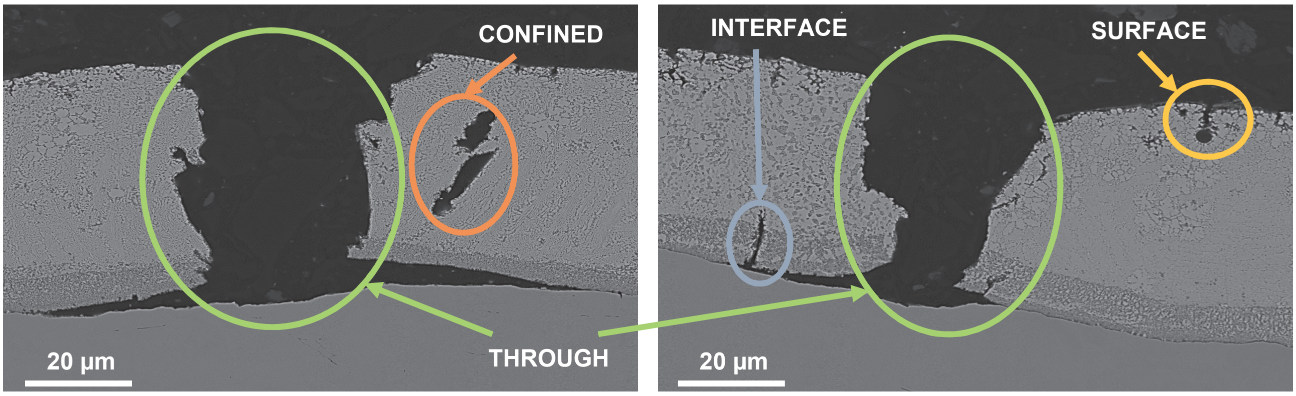

Figure 2 Classification of crack types as seen on Zn5Al0.5Mg alloy bend to 180°, scanning electron microscopy image composed using back scattered electrons

Figure 3 displays the evolution of crack types during the bending process for all examined samples as a dependence of normalised distribution on a crack type on bending angle with highlighted number of exact crack type. **Figure 4** shows the dependence of crack density on distance from apex of the bend for all samples at 180° also with highlighted number of exact crack type.

Figure 3 Relative number of crack types in bended coatings

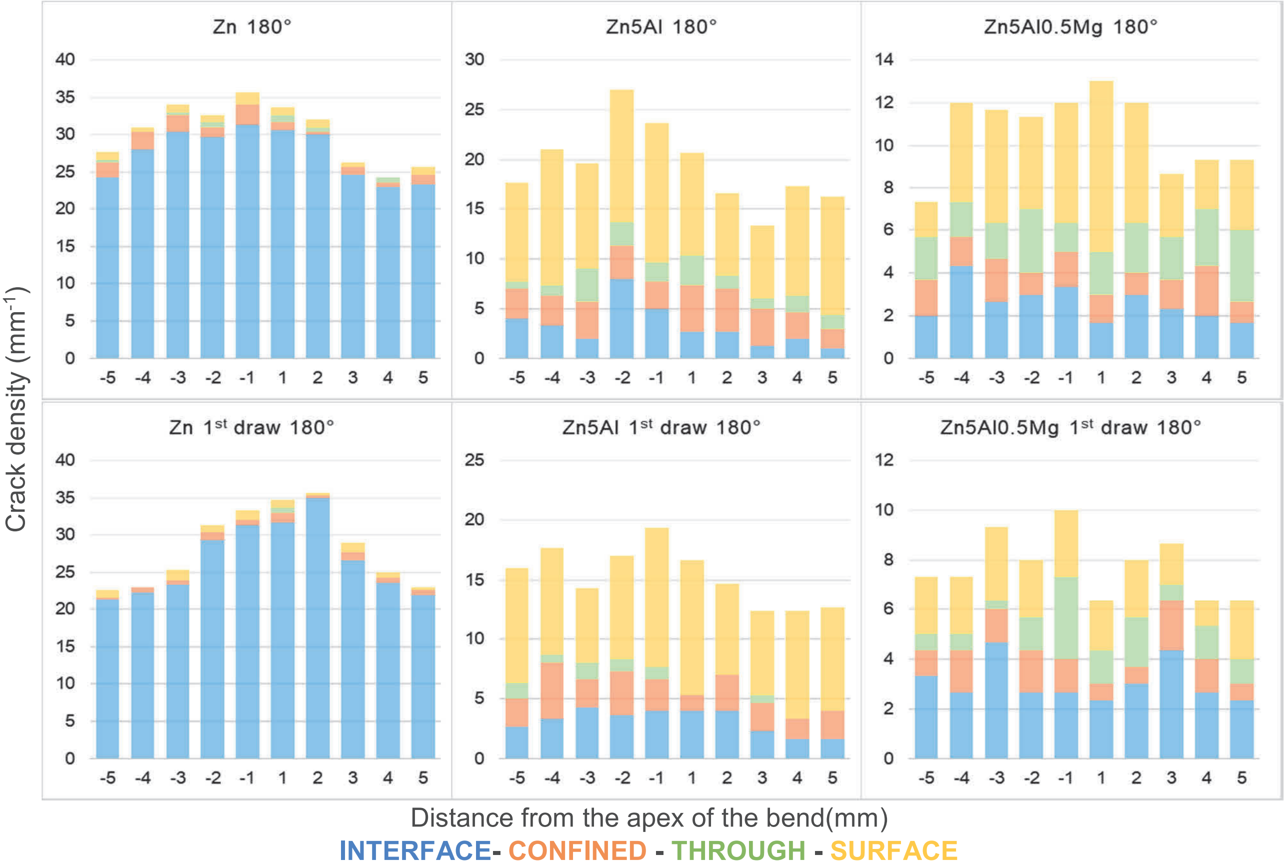

Figure 4 Crack density at 180° bend

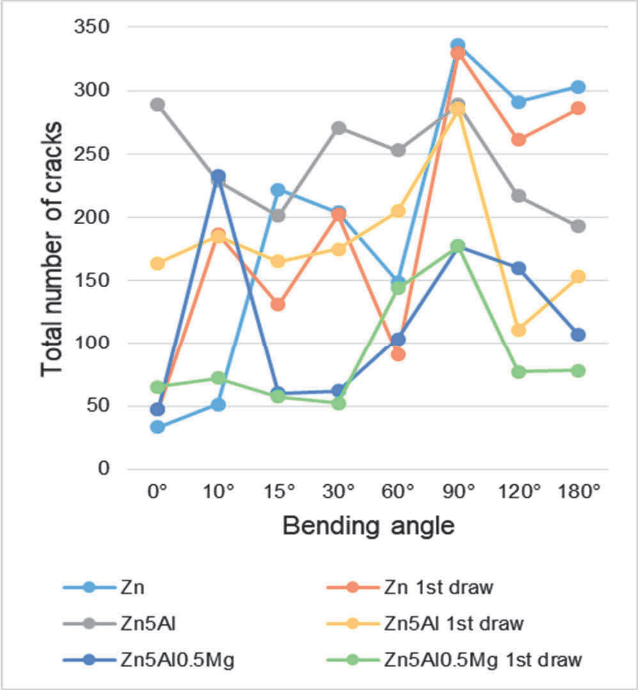

Figure 5 Total number of cracks vs. bending angle

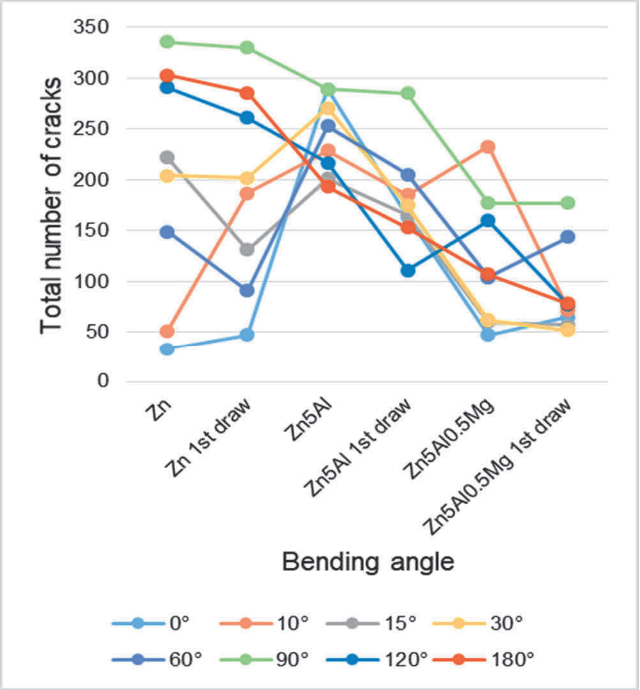

Figure 6 Total number of cracks vs. sample

Cracking initiation and propagation analysis showed that for Zn, Zn 1st draw, Zn5Al0.5Mg and Zn5Al0.5Mg 1st draw wire an initiation of cracks is more common from the substrate-coating interface. On the other hand, it is more common for Zn5Al and Zn5Al 1st draw wires that cracks start to appear at the surface. According to Tzimas and Papadimitriou [5] all cracks initiated at the surface-coating interface propagate towards the free surface of the coating since the strain at the tip of the crack closer to the surface is larger than the strain at the other tip of the crack near the substrate.

Taking in to consideration that a total number of cracks within the coating strongly depends on applied load, a Ploypech's load vs. bending angle dependence [7] could be modified to total number of cracks vs. bending angle dependence (**Figure 5**) even though the power trend was not similar to Ploypech's (due to differentiation in samples and experimental procedures). A maximum can be seen at 90°. This is even more evident in **Figure 6** where line for 90° is at the top except for sample Zn5Al0.5Mg which tends to form numerous cracks at as low angles as 10°. Lower number of cracks at bending angles above 90° indicates higher tendency of propagation and joining of cracks rather than formation of new cracks.

The coatings Zn and Zn 1st draw were most susceptible to the formation of interface cracks as can be seen in **Figure 7**. Since the coating is composed of an Fe-Zn alloy layer and ductile zinc layer, coating-substrate interface is the first location for cracks to appear. This is caused by the average thickness (several μm) and mechanical properties of the intermetallic phases that form the Fe-Zn alloy layer of pure Zn coatings [8]. For all other coatings, the interface cracks formation correlated more with the bending process with maximum observed at 90°, except for Zn coating where the formation of interface cracks continues until 180°.

Confined cracks are mostly present in Zn5Al and Zn5Al 1st draw coatings (**Figure 7**). This correlates with its microstructure where high Al layer builds a greater cracking barrier. Most of the confined cracks develop at the high Al layer - low Al layer interface. Rest of the coatings follows similar trend in confined cracks formation with smaller ascent at 10° and the maximum at 90°. Extreme population exceeding 120 confined cracks at 10° bending angle (**Figure 7**) in case of Zn5Al0.5Mg is due to random fluctuation in case of one out of three inspected wires where number of confined cracks appeared to be 5 times higher.

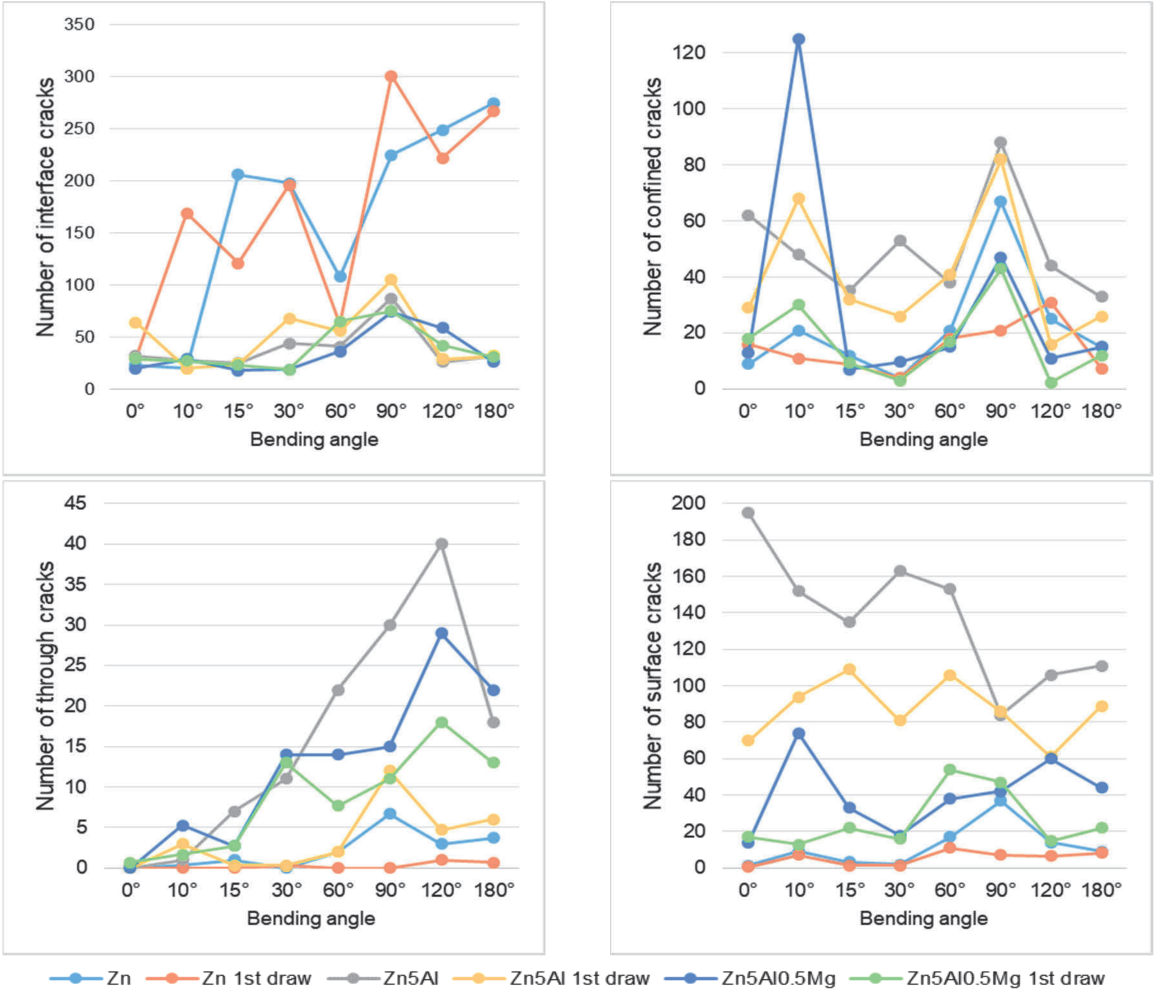

Figure 7 Evolution of four classes of cracks

Through cracks are the most dangerous cracks since they allow the environment to directly influence the substrate. This can lead to sever deterioration of the material. **Figure 7** follows the evolution of through cracks which start to appear at 10° where Zn5Al0.5Mg coating contains the highest count with 5 through cracks. At 30° the total number triples for Zn5Al, Zn5Al0.5Mg and Zn5Al0.5Mg 1st draw. At 90° Zn and Zn5Al 1st draw reaches their maximum with 7 and 12 through cracks respectively. The highest number of through cracks has Zn5Al, followed by Zn5Al0.5Mg and Zn5Al0.5Mg 1st draw coatings with 40, 29 and 18 through cracks respectively. The performance in this point of evaluation proved Zn 1st draw wire with maximum of 1 through crack at 120°. Even though Zn5Al has the highest number of through cracks, Zn5Al0.5Mg 1st draw coatings performed incomparably worse, since they produced very wide through cracks with high tendency to delamination.

Surface cracks present a great risk for the coating since they open the coating to the environment. Least resistant to surface cracks (**Figure 7**) are Zn5Al and Zn5Al 1st draw coatings with relatively great difference between them compared to the rest of the non-drawn and 1st draw coating pairs. The best performance was presented by Zn and Zn 1st draw, probably due to the homogeneous Zn layer.

CONCLUSION

- Cracks initiate at the substrate-coating interface for Zn, Zn 1st draw, Zn5Al0.5Mg and Zn5Al0.5Mg 1st draw wires. For Zn5Al and Zn5Al 1st draw wires the cracks initiation is more common at the surface.

- The maximum of total number of cracks occurs for all samples at bending angle of 90°. The highest total number obtained by Zn and Zn 1st draw is approximately one fifth more than for Zn5Al and Zn5Al 1st draw and two times more than for Zn5Al0.5Mg 1st draw.
- Most susceptible to interface cracks are Zn and Zn 1st draw wires with up to three times more cracks than the rest of the samples which behaves similarly.
- Most susceptible to confined cracks are Zn5Al and Zn5Al 1st draw wires producing two to three times more confined cracks than the rest of the samples. The best performance showed Zn 1st draw wire.
- Most susceptible to through cracks was Zn5Al having a third more through cracks than Zn5Al0.5Mg wire and three times more than Zn5Al0.5Mg 1st draw wire. The best performance showed Zn 1st wire with only 1 through crack at its maximum.
- Most susceptible to surface cracks is Zn5Al wire followed by Zn5Al 1st draw. Four to five times less amount of surface cracks occurs in Zn5Al0.5Mg and Zn5Al0.5Mg 1st draw wires. The best performance showed Zn 1st draw wire with lowest maximum of 11 surface cracks at 60° bending angle.
- Compared to non-drawn wire, 1st draw wires have generally greater cracking resistance in all type of cracks except the interface cracks where the differences between each bending angle is so substantial that these are not comparable.

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