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Metallurgical Failure Analysis on a Suspension Clamp in 154kV Electric Power Transmission Tower

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Abstract

Failure of a suspension clamp made of hot dip galvanized cast iron in 154kV transmission tower was investigated. Metallurgical analysis of a crack of the clamp was performed using a digital microscope, an optical microscope, and a scanning electron microscope. It was revealed that the crack surface was covered by continuous zinc layer. Distinctive casting skin was found underneath both the outer surface and crack surface. The result showed that pre-existing crack had been formed in the fabrication, and liquid metal embrittlement during hot dip galvanization may assist crack propagation.

Keywords: Suspension Clamp, Manufacturing Defect, Casting Skin, Cast Iron, Decarburization, Hot Dip Galvanizing, Liquid Metal Embrittlement

I. Introduction

A suspension clamp is mechanical component in hanging fittings of overhead power line. Although it is generally designed with high factor of safety, any failure of suspension clamp might lead to serious problem in power system [1,2].

Cast iron is one of the most widely used materials on mechanical fittings in the electrical industry. Its cost effectiveness on mechanical properties is well known especially for complex-shaped fabrication. Cast iron features a good combination of tensile strength, impact resistance and damping capacity. For enhanced environmental resistance, hot dip galvanizing is the most frequently used in the industry, which covers the surface of the metal with protective material.

In manufacturing process of cast iron, casting skin is generated by metal-mold interaction, which indicates decarburized layer of cast iron in the sub-surface of casting. The microstructure underneath casting surface is different compared to the bulk regarding amount of graphite, graphite morphology and matrix structure [3]. Oxidation in the interface with mold can be followed by decarburization in the casting or hot dip galvanizing process [4-6]. The casting process of white-heart malleable cast iron distinctively comprises decarburization and carburization process performed in oxidizing atmosphere [7].

Hot dip galvanizing is an efficient way to protect the base metal in the corrosive environment [8-10]. Hot dip galvanizing comprises several chemical processes such as degreasing, pickling, and fluxing prior to galvanizing [11]. Occasionally, cracking occurs in the process of hot dip galvanizing such as distortion cracking, hydrogen embrittlement, strain-age embrittlement, and liquid metal embrittlement [12, 13]. Those cracking is usually covered by the zinc coating and not detected until operating stress applied in service [13].

In this paper, the crack in a hot dip galvanized suspension clamp made of cast iron was investigated. The cracking was discovered in the inspection after 40-year service. Root causes of the cracking of the clamp were analyzed by metallurgical analysis. Sub-surface microstructure beneath the crack surface was metallurgically investigated relating with fabrication issues. Simple preventive action was suggested for the manufacturers.

II. EXPERIMENTAL

Visual observation on the crack was performed with digital camera. Chemical analysis of base material was obtained using an optical emission spectrometer. Fracture surface was observed with a digital microscope. Its cross-section was metallurgically examined using a digital microscope, an optical microscope, and a scanning electron microscope. Chemical elements composed of cracked region by elements was obtained by electron dispersive spectrometer.

III. result and discussion

A. Visual observation

Fig. 1 shows fractured suspension clamp. About 50mm transverse crack was found in a shoulder where a U-bolt clamp being inserted into nearby as shown in Fig. 1(d). The product was corroded to some extent overall.

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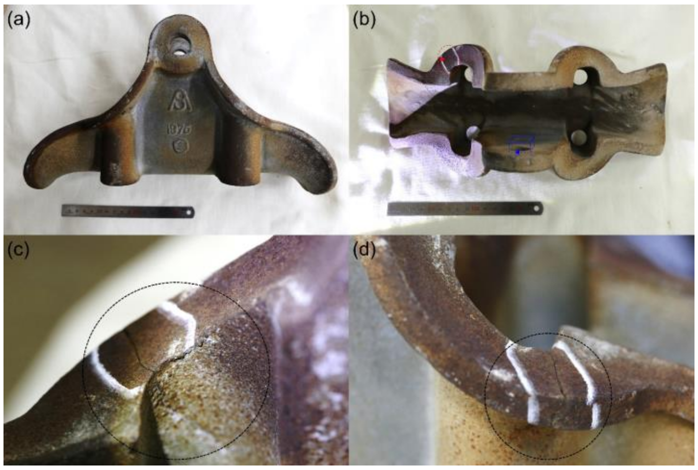

Fig. 1. A cracked suspension clamp (a) Front view (b) Top view (c) Inner view of a shoulder (d) Outer view of a shoulder

TABLE 1
Chemical composition of the suspension clamp obtained by an optical emission spectrometer

Element	C	Si	Mn	P	S	Ni	Mg	Cu	Fe
The clamp	3.78	1.06	0.60	0.007	0.11	0.03	0.004	0.12	Bal.
Malleable cast iron [14]	2.2-2.9	0.9-1.9	0.15-1.2	0.02-0.2	0.02-0.2	-	-	-	Bal.
Compacted graphite cast iron [14]	2.5-4.0	1.0-3.0	0.2-1.0	0.01-0.1	0.01-0.03	-	-	-	Bal.

B. Chemical analysis

Chemical composition of material used for suspension clamp was obtained by optical emission spectrometer. The location examined is shown in Fig. 1(b) which is indicated by the blue lines. The product was made of cast iron and its composition by elements in comparison with typical malleable and compacted graphite cast iron [14] are listed in Table. 1.

C. Fractography

Fracture surface was entirely covered with oxides as shown in Fig. 2, so that the traces of crack propagation were not sensible. For assessing metallurgical characteristics of the fracture surface beneath the oxides layer, cross-section of a black rectangular 'A' in Fig. 2 was sectioned. The analysis will be addressed in the following section.

D. Metallurgical Analysis

Cross-section of fracture surface 'A' in Fig. 2 was observed by microscope as shown in Fig. 3. Note that the fracture surface was covered with continuous white colored layer under black layer indicated by the red arrow in Fig 3(a). The chemical compositions of the white and the black layer using EDS are listed respectively in Table. 2 and 3. It was revealed that the white layer consists mostly of zinc while the black layer zinc and oxygen. In morphology, the columnar layer in white below the black seems zinc-iron intermetallic compounds comprising zeta (ζ) phase which features numerous tiny crystals [8, 12, 15] in Fig. 3(b) and 4.

Fig. 2. Fracture surface obtained by digital microscope

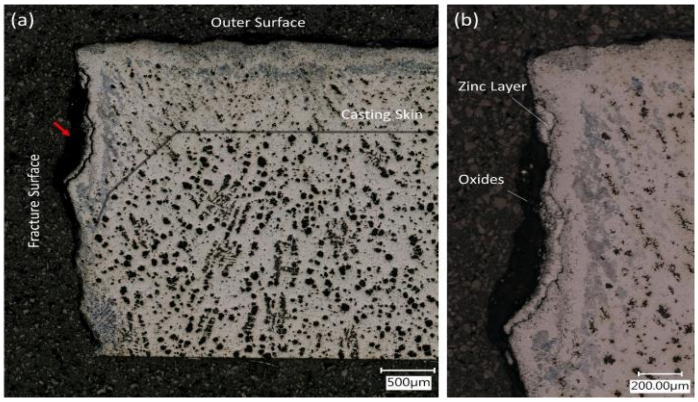

Fig. 3. Digital micrograph of cross-section of fracture surface etched by 4% nital solution (a) low magnification (b) Higher magnification of the region indicated by red arrow in Fig. 2(a)

TABLE 2
Chemical composition of 'Zinc Layer' in Fig. 3(b)

Element	Composition (w.t%)
O	3.51
Fe	7.81
Zn	88.69

TABLE 3
Chemical composition of 'Oxides' in Fig. 3(b)

Element	Composition (w.t%)
O	33.29
Al	1.23
Cl	0.41
Fe	2.38
Zn	62.69

Furthermore, the distinctively decarburized zone near the surface was noticeable in Fig. 3(a). In Fig. 3(b), The covering layers on the fracture surface and microstructure beneath the layer were more visible in detail. The microstructure of the sub-surface consists of ferritic rim, pearlitic layer and depleted graphite. These features

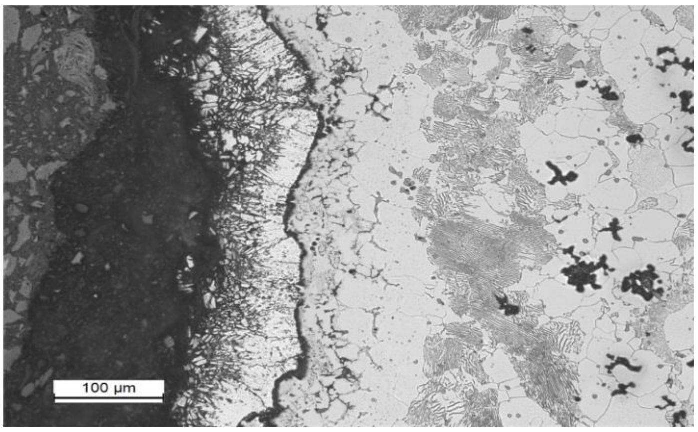

Fig. 4. Microstructure of cross-section of the fracture surface obtained by optical microscope which shows covered with zinc compound layer and oxides.

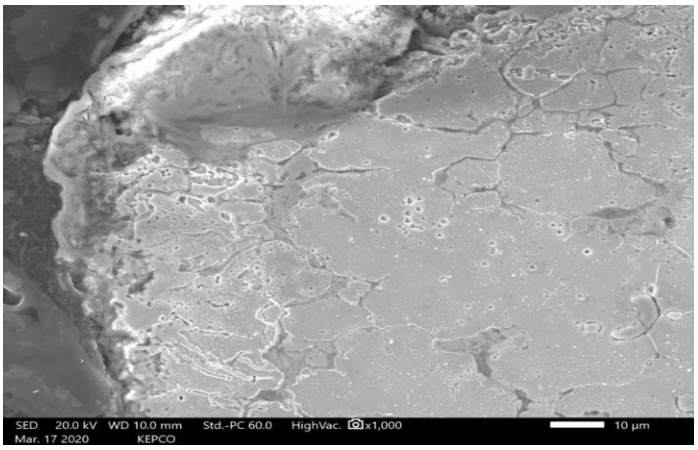

Fig. 6. Scanning electron image of cross section of the fracture surface near outer surface which reveals multiple intergranular cracks

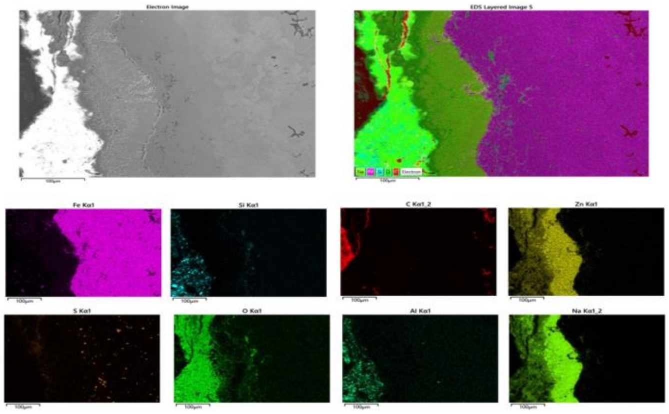

Fig. 5. Elemental mapping of the cross-section of the crack surface which shows thick zinc coated layers on the S curve shaped iron surface and graphite depletion zone beneath the zinc coated layer.

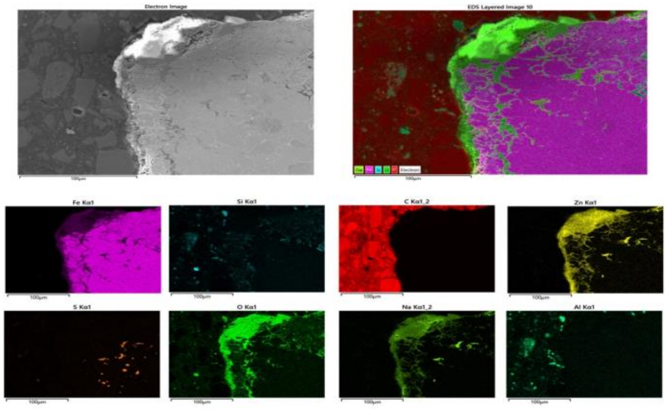

Fig. 7. Elemental mapping of the cross-section of the crack surface in the vicinity of the outer surface at which zinc was penetrated in the intergranular cracks.

are clearly distinctive in comparison with microstructure of the base metal. All the features can be formed through decarburization of the inner matrix microstructure, which are composed of casting skin in the casting. The casting skin exist beneath not only outer surface but also fracture surface. Fig. 4 shows the microstructure of the surface and sub-surface of the crack more in detail.

Fig. 5 shows the distribution of the chemical elements in the vicinity of the crack surface. The iron abundant area must be base metal. Carbon was detected partially in the inner region where graphite exists in Fig 4 while sulfur was distributed in condense manner. Above the iron region, there is a continuously distributed zinc and sodium layer which is probably a hot dip galvanized coating layer. The outer layer is composed of environmentally abundant mixtures such as aluminum, silicon, and oxygen.

E. Discussion

It is known that casting skin such as ferritic rim, graphite depletion is generated in the casting process by metal-mold interaction due to oxidation [3]. The casting skin appearing on the subsurface beneath the crack clarify that the crack occurred during casting process. Furthermore, the uniformly distributed zinc layer on the fracture strengthens our hypothesis that the initial crack had existed before hot dip galvanizing.

More interestingly, intergranular cracks filled with zinc were found as shown in Fig. 6 and 7. Filled zinc in the in Ztergranular crack tells us that crack was generated after casting process, and before/during hot dip galvanizing. These intergranular cracks can occur by hydrogen embrittlement, liquid metal embrittlement [16, 17], or temper embrittlement [16, 18, 19]. Hydrogen embrittlement is related to acid pickling and fluxing with $ZnCl_2$ and NH_4Cl. However, it only happens in high strength steel and iron. When surface crack is related to galvanizing, liquid metal embrittlement (LME) is important degradation factor [17]. LME often features the crack filled with zinc layer. The pre-requisite for the LME cracking includes material susceptibility, stress concentration factor, high level of residual stress, and the presence of molten metal such as zinc in this case [1, 7]. High roughness generated by sand casting followed by fluxing in galvanizing can contribute to liquid metal embrittlement as high stress concentration factor [8, 17]. High stress concentration factor due to micro-crack by metal-mold interaction or pre-existing crack boosts LME significantly. However, LME mostly occurs with high tensile strength steel and iron [12, 21, 22]. Relating to LME in mild strength material, it happened when the significant residual stress had existed [23]. LME is principally only crack propagation phenomenon [16, 24]. For complex shaped structure, stress due to differential thermal expansion during hot dip galvanizing can be the driving force to the LME [21]. In mild strength material, an intergranular crack was not driven by LME but by other embrittlement such as temper embrittlement [21]. Hot dip galvanizing temperature which is about 450°C corresponds to the typical range of temper embrittlement [18-20]. Especially for cast iron, high silicon and sulfur which usually manipulated in casting as carbon manipulator can influence temper embrittlement in severity [20]. It had not been reported that liquid metal cracking in hot dip galvanizing made the sub-surface beneath the crack decarburized. In the contrast to this, the cracking with filled zinc have been reported many times which is attributed to pre-existing crack irrespectively of the LME [12, 21, 25]. Subsequently, the importance of LME mechanism in this case is limited because it was not the root cause to main crack initiation. Nonetheless it might influence not only secondary crack propagation in Fig. 6 but also propagation of pre-existing crack. For remedial action of the root cause of failure, casting defects such as hot tear, cold shut should be prohibited by casting simulation which can perform residual stress analysis [27], and optimize the design of gate, feeding, and mold [26]. Furthermore, every pre-existing crack would be filled with molten material after hot dip galvanizing. Afterwards non-destructive testing would not be effective for the crack except several expensive methods for instance, X-ray inspection. Consequently, it is important that the foundry manufacturer inspect the casting defect prior to galvanizing and prevent from damaging in the galvanizing process through reliable quality control process in the procedures. Roughness enhancement through elimination as-cast skin by machining [28] or mold coating improvement [29] would be beneficial in lowering stress concentration for liquid metal embrittlement. Temper embrittlement during hot dip galvanizing can be alleviates by some heat treatment. Low cooling rate during hot dip galvanizing and pre-treatment before galvanizing which heated the product up to about 650°C and quenching prevent embrittlement [18-20].

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