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Influence of hot dip galvanizing on fatigue behavior of welded steel joints

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Abstract of master's thesis

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Abstract

This thesis investigates the effect of hot dip galvanizing (HDG) on fatigue strength of fillet welded joints of S355 structural steels. HDG is a surface treatment that allows protecting components from corrosion, but its effect on the fatigue strength of the welded joint is not well understood.

In this thesis, a comparative study has been carried out between hot dip galvanized fillet welded cruciform joints made by S355 and non-galvanized welded joints characterized by the same geometry. Microstructures and the fracture surface of fatigue test specimens have been studied macroscopically and microscopically. The effect of galvanizing on microstructure, penetration of zinc to steel and its effects on initiation of crack has been investigated. Based on conducted fatigue tests, reduction of fatigue strength of galvanized samples comparing to bare metal is not considerable in low cycle fatigue regime. Using scanning electron microscopy (SEM), microstructure investigation has both revealed micro cracks on coating and also the notches located close to the welding toe. A few deep cracks were observed close to the weld notches. In high cycle fatigue regime, these cracks have the ability to propagate and lead to reduction of fatigue limit. Delamination and debonding between coating and substrate, which are potential sites for stress concentration and crack initiation, were observed. Based on this study, it has been concluded that HDG can reduce fatigue limit in high cycle load. Further investigation is needed on this subject.

Keywords hot-dip galvanizing, fatigue strength, crack initiation, debonding, delamination, welded Joints, microstructure, optical microscopy, SEM

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Nomenclature

N_f	Fatigue Life
N_i	Crack Initiation Cycle Number
N_p	Crack Propagation Cycle Number
R	Stress Ratio
t	Plate Thickness
σ_{max}	Maximum Stress
σ_{min}	Minimum Stress
σ_m	Mean Stress
$\Delta\sigma$	Stress Range
σ_a	Stress Amplitude
a	Weld throat

Abbreviations

HDG	Hot Dip Galvanizing
SEM	Scanning Electron Microscope
MAG	Metal Active Gas
N	Number of Cycles
R	Load Cycle Ratio
LME	Liquid Metal Embrittlement
LMC	Liquid Metal Cracking
HE	Hydrogen Embrittlement
S	Constant Amplitude Stress Level
HAZ	Heat Affected Zone
DPN	Diamond Pyramid Number
BHN	Brinell Hardness Number
HR	Rockwell Hardness Number
HV	Vickers Hardness Number
BSE	Backscattered Electron Images
EBSD	Electron Backscatter Diffraction
EDS	Energy Dispersive Spectroscopy
LCF	Low-Cycle Fatigue
HCF	High-Cycle Fatigue
CL	Cathodoluminescence

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1. Introduction

1.1 Background

Different kinds of structural joints such as welded joints and bolted joints are widely used in various industries, and for preventing them against corrosion, HDG is often used. HDG is one of the most efficient and economic ways of protecting steel against corrosion. This has been the most common practice for about a century as it is safe and meets resource preservation for the steel industry [1]. HDG can be successfully used in large range of applications, in particular when iron or steel are used. Among them steel wires for bridges, automotive industries, construction and steel structures can be mentioned [2]. The aim of galvanization process is to protect the surface of the material from corrosion by depositing a layer of metallic zinc. In this process, a metallic bond between steel and metallic zinc is obtained by immersing steel in a zinc bath at temperature about 460°C.When the material is introduced into the zinc bath and then removed, several changes in chemical composition and mechanical structure can occur. These changes produce a new structural arrangement on zinc substrate and are usually revealed by the generation of cracks in the zinc layer [3]. Although HDG is recognized to be one of the most effective techniques to combat corrosion, cracks can arise in coating layer. These cracks can affect the life of the coated material and decrease the lifetime service of the entire structure [4].

However, during the past decade, many investigations have revealed cracking in hot dip galvanized construction or structural steels. While the monotonic behavior of steel is not greatly affected by the presence of zinc layer, except for yield stress, under cyclic stress the fatigue strength is usually reduced [5]. Some authors correlated the fatigue strength reduction to the coating thickness of the zinc layer [6]. In one research, some recent failures of HDG welded structures and HDG high strength steel screws are presented. Structures were made of S_{355} grade steel and Metal Active Gas (MAG) process was applied for welding. Large cracks were observed in vicinity of welds after HDG [7].

One of the other researches, under the leadership of the Technische Universität Dortmund was initiated in order to investigate the effects of HDG on the fatigue performance of S_{355} steel and composite bridge construction [8]. The aim of the project was development and presentation of the necessary scientific and technical findings to enable the use of HDG for construction elements used in bridge construction that are subjected to dynamic loads. After fatigue test, it was possible to verify that the reduction of fatigue strength is not considerable, but HDG significantly lessens the fatigue limit of S_{355} construction steel. All specimens show a noticeable reduction of the fatigue limit in comparison to the corresponding non-galvanized specimens. Possible reasons for this reduction of the fatigue limit due to HDG could be a diffusion-controlled attack on the base material by molten liquid zinc during the

galvanizing process. By SEM analysis, it is observed that there is not any sign of damage to the base material due to an attack by the molten zinc, also diffusion of the elements of the molten zinc during the galvanization process (liquid metal assisted cracking) could not be proven. In addition the metallographic research results based on specimens tested in cycle tests indicates that the cracks in coating can grow into the base material when subjected to fatigue load. Formation of cracks in the base material through stress overload caused by micro-notches is assumed to be the cause of reduction in fatigue strength causing a premature failure of the construction element [8].

In another research, fracture mechanism of steel structures was investigated using optical microscope. Structures were made of S_{355} grade steel and welding has been done with MAG process. The cracks initiated in the notch at the interface between the weld and base metals, e.g. in the HAZ. The cracks propagated perpendicularly from the HAZ into the base metal. From the comparison of fatigue tests on galvanized and non-galvanized specimens, it could be shown that, the HDG caused a significant reduction of the fatigue limit of S_{355} construction steel. According to the status of the research, the cause for the reduction is the structure of the zinc coating with its micro-notches in the form of cracks in the coating. The proven reduction in the fatigue limit has no negative impact on the S-N curves according to DIN EN 1993 due to the standardized slope of the S-N curve and the related shortfall of the actual endurance and fatigue limits [3]. Another researcher considered that liquid metal assisted cracking or it can be an effect of the micro cracks in the zinc coating on the stress state of the specimen and this phenomenon reduces the fatigue resistance [9].

In one research by appropriately employing the Kitagawa-Takahashi diagram was proved that the zinc layer does not affect the fatigue strength behavior of the considered steel if the thickness does not exceed the threshold value of 60 mμ [10]. Besides, in above researches many authors have not supported any specific correlation of loss in the fatigue strength due to the coating thickness. In another research, the effect of zinc galvanization on the microstructure and fracture behavior of low and medium carbon structural steels has been investigated. In this research, they have found carbon structural steels lost their fracture toughness because zinc and zinc bath additives that migrated to crack tips are responsible for the loss in ductility. The phenomenon of liquid metal embrittlement (LME) is suggested to have taken place [11]. Boyed and Hyler in their work on hot zinc coated fasteners found out that resistance to crack propagation was reduced and they attributed this to hydrogen phenomenon [12]. Regarding hydrogen entrapment, it is rationalized that during the HDG hydrogen ejected from the steel is held in zinc coating. Zinc hot-dip coatings entrap hydrogen at the elevated temperature of the zinc bath 454°C -465°C. It has been proposed that hydrogen gets released from traps during hot-dipping and is prevented from escaping by the intermetallic layers that form on the steel surface during coating in the hot bath [13 and 14].

Bergengren and Melander presented results of fatigue test for high strength steel. Fatigue degradation is explained by cracking from coating cracks and coating thickness influence is investigated. Moreover, for their steel, the thicker coating gave

the shorter lifetime [6]. De la Cruz and Ericsson state a 9% decrease in fatigue strength after HDG for hot rolled bar 20mm in diameter [15]. They account it by either a cracking in coating layers or hydrogen embrittlement after pickling. Regarding possibility of hydrogen embrittlement Carpio *et al.* investigated the influence of the surface preparation operations on mechanical properties. Hydrogen content measurements, after each operation, make them assume that some hydrogen could concentrate at coating intermetallic layers surfaces. It can be a possible mechanism for S_{355} steel embrittlement, after HDG [16].

While in the literature some results from fatigue tests made on un-notched specimens can be found, very few results are available dealing with notched components and welded joints. Two papers have reached the conclusion that the main effect of HDG in welded joints is due to geometrical effects and the thickness of the zinc layer does not influence the fatigue life of the welded components [17, 18]. On the other hand, some authors did not find any correlation in terms of loss of the fatigue strength due to the HDG [19]. One research on welded structure steel subjected to HDG mentioned that the coated specimens have slightly less fatigue strength than uncoated specimens, but their strength is in the range admitted by Eurocode [4]. Finally, we can say that the effect of HDG on fatigue strength of steel materials is not clear yet, especially regarding welded joints, only few results about the effect of HDG on the behavior of welded structural steel are available. The main purpose of this thesis is to partially fill this lack of information. This thesis has only investigated the effects of HDG on cruciform fillet welded joints of material S_{355}.

1.2 Objectives and Scope

The objective of this thesis is to predict and investigate effect of HDG on fatigue resistance of S_{355} structural steel welded joints by means of fatigue test. Moreover, microstructure tests on surface fracture after fatigue test have been done to investigate key effective factors in reduction of fatigue resistance.

To do so, the following studies have been under taken in this thesis:

- Fatigue test of fillet welded samples, welding by MAG process have been measured by servo-hydraulic test system with determined loads. A comparison has been carried out between hot dip galvanized fillet welded cruciform joints made by S_{355} structural steel and non-galvanized welded joints characterized by the same geometry to investigate the effect of HDG on fatigue strength.

- Vickers hardness test for three selected specimens have been done to check the changes in hardness after galvanizing and effect of galvanizing in ductility of the base metal. As LME is one of the possible reasons for reducing ductility and fatigue resistance, by hardness test diffuse of any additive in base metal can be checked.

- Metallography and SEM test of specimens fracture surface were done to investigate key factors that influence the fatigue resistance. Micro cracks and Zn diffusion, crack initiation and crack propagation have been investigated and the possible reasons for fatigue reduction have been considered.

1.3 Research Limitations

In this study, fatigue strength was tested for ten galvanized steels and four bare steels and all tests were performed at low cycle regime. To investigate changes in fatigue limit, we need some other samples to test them at high cycle regime to get a more accurate result. In addition, it is better to test two different specimens with one stress magnitude and compare the fatigue strength test results of the two specimens. Overall to obtain better results we need to test more specimens at different loads at low cycles and high cycles.

We have conducted hardness test to check the material changes after HDG. During hardness test, we realized that hardness of one of the tested samples was different from other two and the hardness value was in S_{235} hardness range. This raises the question of reliability of some material specifications. It is better to check the hardness of all the samples and find out the exact material of the samples. Since galvanizing is a type of heat treatment and heat treatment has positive effect on mechanical properties such as fatigue resistance [20], it is good to have more specimens to remove the coating from their surfaces and then to perform the fatigue test. By this experiment we can realize how much the existing micro cracks in the galvanized coatings affect the fatigue strength and also we can compare the effect of heat treatment with the effect of galvanizing on the fatigue strength.

In addition, it is advisable that some specimens have cut before fatigue testing and have a microstructure inspection of coating and cracks to indicate that cracks are already present in the coating due to galvanization and cold working. In order to explain the origin of these cracks, regular metallographic investigations were performed by using optical and scanning electron microscope on galvanized specimens that have been cold drawn. The thickness of galvanizing and the galvanizing composition are the other limitations. If we had more specimens, we could investigate the effect of the coating thickness layer on fatigue strength. In addition, effect of bath chemical composition, immersion time and temperature on producing crack after galvanizing can be investigated in further researches.

1.4 Research Challenges

Since test specimens are fillet-welded joints, we must first prove that the welded specimens are without any defects. During the fatigue test, many samples have been broken from weld roots. This causes unreliability in the tests. The model of test

specimen design is based on fillet welding of two parts of material. The weld area is the area of stress concentration that can lead to failure. After fatigue testing, specimens were cut and the microstructure of material has been investigated in HAZ and galvanized area. There are some problems with this type of welding design. Diffusion in the weld is incomplete, and causes the stress concentration which is suspended to crack initiation. This means that fillet weld defects shortens the crack start time and during fatigue test there is a high probability that specimens break from the root. In addition, the investigation shows that beveling has not been conducted on the welded parts. In the welding procedure, the parts which are welded together must first beveled. Since the design of the test specimens is without bevel and is not based on WPS, it seems this design is unacceptable and may not give reliable and useful results due to incomplete diffusion in welding and stress concentration in the welded area. These types of defects can affect the results of fatigue strength. Welded specimens should be tested before fatigue and only sound welds can be selected for fatigue testing. As material fails at stress concentration location and welding region is the stress concentration area, after welding and before HDG, these areas would be removed.

In addition, it should be noted that the galvanizing process must be done in a suitable condition. Before galvanizing the surface of base material, it is necessary to clean it for better adhesion between coating and the base metal. Segregation between galvanized steel and the base steel can cause debonding and can lead to crack initiation. Preparation of the material surface before galvanizing is crucial for adhesion of coating. Sufficient adhesion of coating prevents the coating against debonding [21]. Debonding can cause holes and gaps between the coating layer and the base material, which is capable of stress concentration and lead to the initiation and propagation of cracks [22]. Therefore, surface preparation before HDG is important for testing.

1.5 Thesis structure

After this introductory in chapter 1, research method applying in this thesis including welding definition and welding defects, HDG, HDG defects, fatigue, hardness and microstructural tests will be introduced in chapter 2. Experimental methods, geometry of the specimens, specimen selection, preparation for testing and conducted tests are explained in chapter 3. In Chapter 4, experimental results for proposed experimental methods in the previous chapter have been presented and comparison between fatigue strength of galvanized material and bare material is investigated. In addition, some micrographs showing defects in specimens' microstructures are reported in this chapter. Finally, conclusion and future work is presented in Chapter 5.

2. Characterization of fatigue behavior and mechanical properties of welded joint

2.1 Welding Effect on Fatigue Strength

Welding strongly affects the material by the process of heating and subsequent cooling as well as by the fusion process with additional and different materials. Furthermore, a weld is usually far from being perfect, containing inclusions, pores, cavities and undercuts. The shape of the weld profile and non-welded root gaps create high stress concentrations with widely varying geometry parameters. Residual stresses and distortions due to the welding process affect the fatigue behavior. Therefore, fatigue failures appear in welded structures mostly in the welds rather than in the base metal [23].

Welding is a type of joining process which is widely used in industries. During the welding process, residual stresses can occur in the weld area, either in the HAZ or fusion zone. Residual stresses can change the fatigue life. Welded assemblies, with geometrical imperfections, can also induce residual stresses. Residual stresses removal can only be partially achieved by stress relief methods. Residual stresses can still remain in a welded joint even after some of these stress relief methods have been achieved.

Fatigue is defined as cumulative, localized and permanent damage caused by repeated fluctuations of stresses usually below the static design stresses of the structure. It should be noted, that welded components are less tolerant to the fluctuating loads than their non-welded counter parts for the following reasons:

- Welds contain internal flaws which act as initiation site for crack propagation.
- Welds create external stress raisers which act as initiation site for crack propagation.
- The process of welding introduces residual stresses in the region of weld exacerbating the applied fluctuating stresses [23].

2.1.1 Welding Defects

Welding defects can be defined as the irregularities formed in the given weld metal due to wrong welding process or incorrect welding patterns. Welding defects may occur either outside or inside the weld metal.

The most common weld defects include:

- Lack of fusion
- Lack of penetration

- Porosity
- Slag inclusions
- Crack initiation.

Cracks may initiate due to high stress concentration from these defects under cyclic loading conditions and starts growing. Welding standards proposes acceptable level of weld defects as it is practically inevitable to avoid weld defects [23].

Since the presence of cracks reduces fatigue life and accelerates failure, it is important to avoid all cracking mechanisms in order to prolong the fatigue life of a welded joint. Weld defects, such as inclusions and lack of penetration, should also be avoided as these defects are sources of cracking. One of the most significant factors affecting the fatigue life of the weld is depth of penetration. Incomplete penetration happens when the filler metal and base metal are not joined properly, and the result is a gap or a crack of some sort. This can be described by the minimum throat. The main parameters that affect the minimum throat are essentially weld joint preparations (beveling), weld dress-up, type of weld, welding process parameters like filler material, base material, surface condition of the parent materials, welding process employed, torch angle and welder skills [24]. As material fails at stress concentration locations, these areas would be removed after welding and before HDG .Therefore, the surface preparation before HDG is important for the result of fatigue test.

2.2 Hot Dip Galvanizing

HDG is known as one of the most used techniques for protecting steels against corrosion. HDG is a chemical treatment and process of immersing iron or steel in a bath of molten zinc to produce a corrosion resistant, multi-layered coating of zinc-iron alloy and zinc metal. The process is inherently simple, which is a significant advantage over other corrosion protection methods. When the clean steel is immersed in molten zinc, zinc-based coating layer formation is obtained by diffusion of zinc atoms in iron and vice-versa. It depends on several physical parameters, including bath temperature, immersion time, pre-galvanizing surface temperature, withdrawal speed and chemical parameters, including bath chemical compositions, steel grade and flux chemical composition. HDG like other coatings isolates the steel from the environment. The zinc coating acts as a barrier, preventing oxygen and water from reaching the steel [25].

2.2.1 Surface Preparation Prior to HDG

For HDG, the steel is first clean to remove all oils, grease, soils, mill scales and rust. For cleaning, the steel is dipped into a series of cleaning chemicals. The first chemical is a degreasing bath that removes organic contaminants such as dirt, grease, and oil from the metal. The next chemical used is pickling acid, which removes mill scale and

rust (oxides) from the steel. The last step before galvanizing is dipping the steel or iron into a flux bath, which prevents oxidation of the metal prior to entering the galvanizing bath and also aids the galvanizing reaction in developing the hot-dip galvanized coating [26].

2.2.2 HDG Coating Layers

The coating that develops during the galvanizing process is bonded to the steel virtually becoming a part of the steel itself. During the reaction in the kettle, the zinc interacts with the iron in the steel to form a series of zinc-iron alloy layers.
Figure 1 shows a cross-section of the galvanized steel coating, showing a typical microstructure comprised of three inner alloy layers of iron and zinc intermetallic phases and a layer of pure metallic zinc, the layers becoming successively richer in iron with depth [27].

- The thin Gamma (Γ) layer composed of an alloy that is 75% zinc and 25% iron
- The Delta (δ) layer composed of an alloy that is 90% zinc and 10% iron
- The Zeta (ζ) layer composed of an alloy that is 94% zinc and 6% iron
- The outer Eta (η) layer that is composed of pure zinc

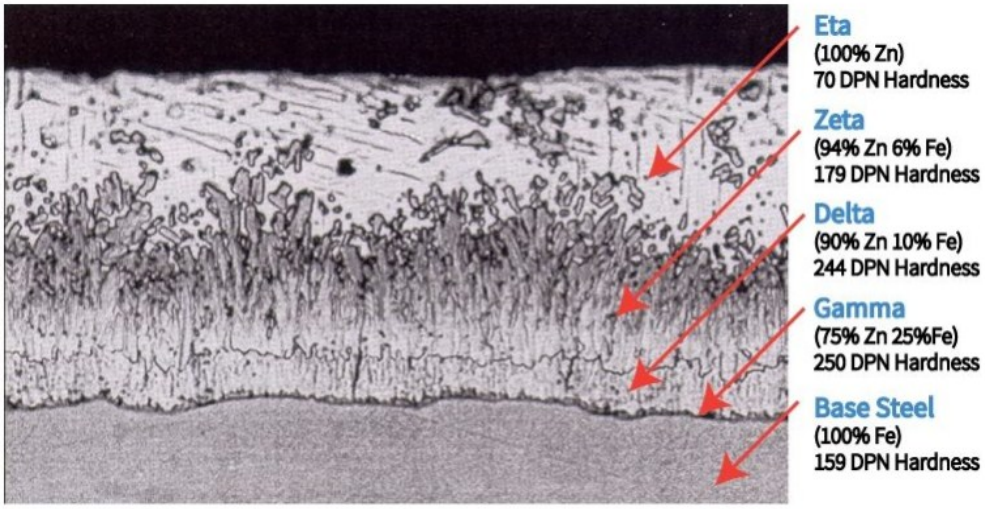

Fig. 1. Photomicrograph of galvanized coating layers [27].

In addition to the chemistry of each layer, the figure identifies the hardness of each layer expressed as a Diamond Pyramid Number (DPN). The DPN is a progressive measure of hardness; the higher number shows the greater hardness. Typically, the

Gamma, Delta and Zeta layers are harder than the underlying steel. The hardness of the inner layers provides very good protection against coating damage by abrasion. The Eta Layer is quite ductile and provides the coating with some impact resistance [27].

Results show that the main damaging mechanism depends on both different mechanical behavior of the intermetallic phases and their thickness. As these phases are characterized by different mechanical and physical properties, these different properties have caused debonding and delamination.

2.2.3 Defects in Galvanized Coatings

In spite of significant advancements in continuous galvanizing technology and the resulting improvements in surface quality of hot dip galvanized and galvanized coatings; producing entirely blemish- free coatings still is a challenging task. HDG of fabricated steelwork involves many variables that can impact on the appearance and characteristics of the finished product. Thus, surface defects are encountered intermittently in all galvanizing lines. Some of these defects are dross inclusions, ungalvanized weld areas, ash staining, delamination, embrittlement, debonding, black spots, drainage spikes and puddling [28].

Most defects are the result of poor substrate surface quality, insufficient strip surface cleaning, poor bath chemistry management and inadequate line equipment maintenance [28]. Some of these defects can be affecting the mechanical properties, as they can make notch area in the surface of material.

1. Debonding

The role of a HDG treatment consists in the deposition of a protective external layer of metallic zinc obtained by immersing the steel in a zinc bath at a temperature of around 460°C. When the material is introduced into the zinc bath and then removed, several changes in the chemical composition and in the mechanical structure can occur. These changes produce a new structural arrangement on zinc substrate and are usually revealed by the generation of cracks in the zinc layer. These cracks can affect the life of the coated material and decrease the lifetime service of the entire structure [4, 28]. The presence of such cracks is illustrated in Fig. 2.

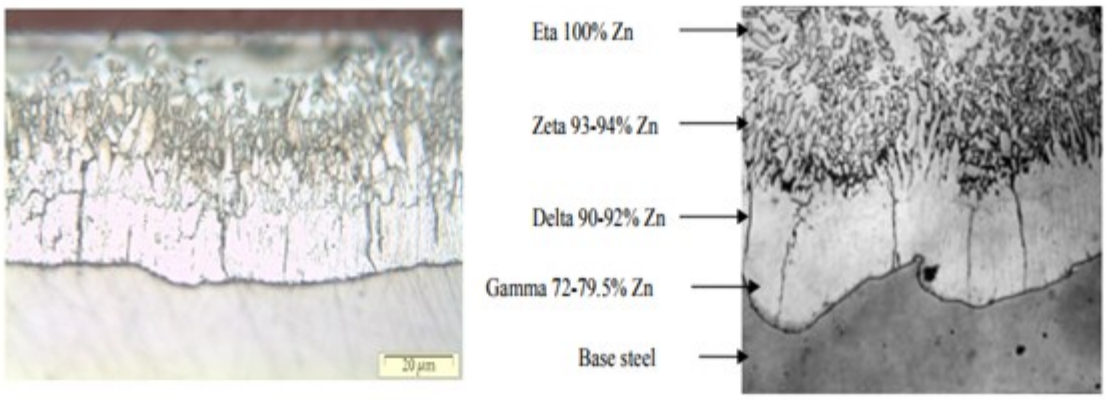

Fig. 2. Cracks in galvanized coating layers [4].

Results show that the main damaging mechanisms depend on the different mechanical behavior of the intermetallic phases and on their thickness. For all the investigated coating conditions, radial cracks are observed. They initiate corresponding to the Γ phase and propagate up to the ζ–η interface. The coating thickness increase implies both an increase of the importance of the cracks in δ and ζ phases and the presence of cracks at ζ–δ interfaces. As a consequence, the increase of coating thickness implies an increase of the ability to a coating-steel debonding damage mechanism, with a consequent loose of the coating adhesion and a decreasing of the capability of the zinc coating to improve the steel corrosion resistance [28].

2. Delamination

Many defects in galvanized coatings are related to problems of delamination also named, ”peeling off” or “shaving” of zinc coating, which happens during the forming operations. “Heat peeling” is the most common reason for the delamination of galvanized coatings. This takes place when the steel, which usually has a high section thickness, is cooled gradually or inadequately during the quenching process and leading to reheating of the coating due to the residual heat in the steel mass. The thermal stresses produced by this differential cooling or heating will develop high shear forces at the steel and coating interface, thereby causing localized delamination of the coating. This will lead to blister formation or, in the worst-case scenario, flaking of the coating from the surface. In general, mechanical delamination occurs on edges or areas in which the galvanized coating experiences higher localized impact or pressure. Thicker galvanized coatings provide improved durability, but once the coating thickness exceeds about 200 microns, the thick alloy layers become more prone to delamination. Very heavy galvanized coatings (more than 250 μm in thickness) may be fragile and delaminate from the surface upon impact and need more cautious handling in transport and installation [30].

3. Ungalvanized Weld Area

The defect caused by ungalvanized weld areas is one of these effective defects on material properties. Coating misses on weld areas are the result of the presence of welding slag on the welds. The fabricator must remove all the welding slag before dispatch to the galvanizer [30].

4. Bare Patches

Uncoated areas on the surface of galvanized work are because of not preparing the surface properly, pickling, insufficient pretreatment in degreasing, and pre-fluxing. These defects can reduce adhesion between material and galvanized coating and can result debonding [30].

5. Embrittlement

Embrittlement of steel as a result of the hot dip galvanizing process is rarely encountered with structural grades of steel. Embrittlement, is the loss or partial loss of ductility in steel that fails by fracture without appreciable deformation. Another way to think about embrittlement is steel cracking without any bending or flexing to indicate the steel is yielding [31].

There are three types of embrittlement encountered in the hot dip galvanizing process.

- Hydrogen embrittlement
- Strain-age embrittlement
- Liquid metal embrittlement

• Hydrogen embrittlement

Hydrogen embrittlement is the most commonly encountered and affects steels which their yield strength is above 800 MPa and can cause brittle fractures under certain conditions. Hydrogen embrittlement occurs when hydrogen atoms from the acid pickling process penetrate the grain boundaries of the steel and steel cracks due to hydrogen trapped between the grains of the steel. Although steel commonly absorbs hydrogen during the HDG process, it is usually expelled due to the temperature of the zinc in the galvanizing kettle. In some cases, however, the grain size of the steel is too small to allow the release of atomic hydrogen. This can later cause cracking due to increased stress at the location of the hydrogen between the grains. Hydrogen embrittlement is not observed until the part is under load, unlike strain-age embrittlement which is observed shortly after galvanizing. In other words, whereas strain-age embrittlement can be observed shortly after galvanizing, hydrogen embrittlement is not seen until the steel has been under load for some extended period of time [26, 31].

- **Strain-age embrittlement**

The most common type of embrittlement encountered in the hot-dip galvanizing process is strain-age embrittlement. Strain-ageing is a process where steel becomes very brittle in areas of high stress when exposed to elevated temperatures. This normally occurs through cold working of the steel prior galvanizing. Cold working can include bending, punching, or shearing the steel. If the stresses from these cold working practices are not relieved prior to galvanizing, they become points of high residual stress during the galvanizing process and can lead to strain-age embrittlement. Strain-ageing can also be caused by impurities in the steel, such as those found in lower quality steels used for reinforcing bar. If a part cracks due to strain-age embrittlement, the cracking occurs immediately after galvanizing but is also often seen at the job site, as in the case of reinforcing bar [26, 31].

- **Liquid Metal Embrittlement**

In LME phenomenon a metal or an alloy becomes brittle, with or without stress, when it is coated (wetted) with a liquid metal. LME is a form of cracking that occurs when molten metals come into contact with susceptible materials. LME also referred to liquid metal cracking (LMC). The molten zinc penetrates the grain boundaries of the steel and fracture under load may result. The liquid metal gets absorbed into the material, causing its bond strength to decrease and cracking along its grain boundaries [31].

2.2.4 Effect of Welding on HDG

The cracks found in galvanized welded steels can be attributed to stresses introduced during the welding of two different thicknesses of steel. The stresses from the welding are from the weld metal itself, as it is typically harder than the base metal, and from the heat applied during welding. The welding process can reduce the ductility of material and increase the hardness of steel in the HAZ and making it more susceptible to brittle fracture. Another factor that could potentially play a role in cracking is hydrogen embrittlement. Steels with bigger hardness are more susceptible to hydrogen embrittlement [26].

Fig. 3. Crack in heat affected zone in galvanized coating [26].

The weld metal and HAZs can obtain hardness values much higher than other areas of the steel. The area with higher hardness is susceptible to hydrogen embrittlement and is highly susceptible to cracking, especially when put under load. Figure 3 shows crack in heat affected zone. The fact that welding stresses are partially relieved in the galvanizing kettle, and the combination of different section thicknesses thermally expanding and contracting at different rates, combined to cause the cracking in welded area. As it is shown in Fig. 3, all of the cracking originated in the weld area, particularly in the HAZs where the hardness values could potentially be high. Also in these areas is the combination of two different thickness steels, which will expand and contract at different rates, adding even more stress to an already highly-stressed area [26].

2.3 Fatigue

The name “fatigue” is based on the concept that a material becomes “tired” and fails at a stress level below the nominal strength of the material. Fatigue cracking is one of the primary damage mechanisms of structural components and is the condition whereby a material cracks or fails because of cyclic stresses applied below the ultimate strength of the material, while applied stresses may be tensile, compressive or torsional, crack initiation and propagation are due to the tensile component. When a mass is repeatedly and cyclically loaded at a location on the material, cracks begin to form. The failure occurs due to the cyclic nature of the load which causes microscopic material imperfections to grow into a macroscopic crack (initiation phase). These cracks spread enough to eventually cause failure and break the material. It can be said that fatigue failure occurs in three stages which are crack initiation, propagation and rapid fracture [32].

Consequently, during the design of a mechanical system, it is important to know these limits. Not only catastrophic fatigue failure could cause a large loss in money due to a poor design but it could result in a loss of lives as well. Critical examples of fatigue failure range can be from train axles to wing cracking on airplanes. A perusal

of the broken parts in almost any scrap yard will reveal that the majority of failures occur at stresses below the yield strength. Fatigue has been estimated to be responsible for up to 90% of the in-service part failures, which occur in industry. Some parameters can affect the fatigue strength, such as load type, surface finish, stress concentration, environment (corrosion), surface treatment, temperature, overload, metallurgical structure and residual stresses. Fatigue strength is reduced significantly by the introduction of a stress raiser such as a notch or hole. Welding is one of the reasons for making stress concentration in material and can decrease fatigue strength [32].

Since fatigue cracks generally initiate at a surface, the surface condition of the component being loaded will have an effect on its fatigue life. Surface roughness is important because it is directly related to the level and number of stress concentrations on the surface. Notches, scratches, and other stress risers decrease fatigue life. Compressive residual stresses from machining, cold working, heat treating will oppose a tensile load and thus lower the amplitude of cyclic loading [32].

2.3.1 Fatigue Test

To perform a fatigue test a sample is loaded into a fatigue test machine and loaded using the pre-determined test stress, then unloaded to either zero load or an opposite load. This cycle of loading and unloading is repeated until the end of the test is reached. Fatigue testing is a specialized form of mechanical testing that is performed by applying cyclic loading to a structure. Fatigue testing measures how cyclic forces will affect a product or material over time, using varying loads, speeds and environmental conditions. A fatigue test is used for the determination of the maximum load that a sample can withstand for a specified number of cycles. All of these characteristics are extremely important in any industry where a material is subject to fluctuating instead of constant forces. The fatigue testing data are often presented in a S-N diagram which is a plot of the number of cycles required to cause failure in a specimen against the amplitude of the cyclical stress. Fatigue tests are typically conducted using servo hydraulic test machines which are capable of applying large variable amplitude cyclic loads of over 100 kN. This data can be used for creating stress-life or strain-life curves [32]. There are two types of fatigue cyclic loads.

- Low Cycle Fatigue Regime (LCF)

Common factors of low-cycle fatigue are low number of cycles to failure and high stress levels. Low cycle fatigue has two fundamental characteristics: plastic deformation in each cycle; and low cycle phenomenon, in which the materials have finite endurance for this type of load [33].

- High Cycle Fatigue Regime (HCF)

High cycle fatigue is useful for materials that experience low applied forces and where deformation is primarily elastic in nature [33].

2.3.2 Fatigue Strength

Fatigue strength is used to describe the material property, which is the highest stress that a material can withstand for a given number of cycles without breaking. Fatigue strength called also endurance strength compare fatigue limit [34].

2.3.3 Fatigue Life

The fatigue life of any specimen or structure is the total number of stress (strain) cycles required to cause failure. This number is a function of many variables, including stress level, stresses state, cyclic wave form, fatigue environment, and the metallurgical condition of the material [32].

Fatigue life formula is:

$$N_f = N_i + N_p \tag{2.1}$$

Where N_f, N_i and N_p are as follow:

Fatigue Life (N_f) - Number of cycles to fail at specified stress level.

Crack Initiation (Ni) – Number of cycles required to initiate a crack.

Crack Propagation (Np) – Number of cycles required to propagate the crack in a stable manner to a critical size.

2.3.4 Cyclic Loading Parameters

To initiate fatigue cracks, three basic factors are necessary. First, the loading pattern must contain minimum and maximum peak values with large enough variation or fluctuation. The peak values may be in tension or compression and may change over time but the reverse loading cycle must be sufficiently great for fatigue crack initiation. Secondly, the peak stress levels must be of sufficiently high value. If the peak stresses are too low, no crack initiation will occur. Thirdly, the material must experience a sufficiently large number of cycles of the applied stress [32, 34].

The load parameters have been identified in Fig. 4.

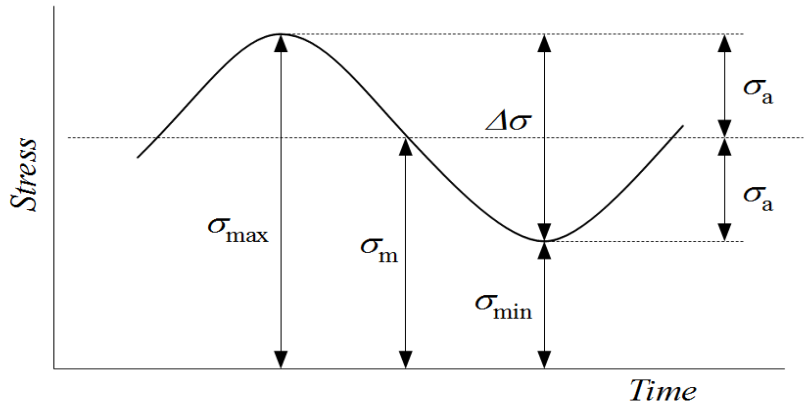

Fig. 4. Schematic illustrating cyclic loading parameters [32].

The nominal stress range will be determined based on the minimum and maximum load level. Tensile stresses are normally considered positive and compressive stresses are considered negative [32].

Mean Stress (σ_m)*:*
$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \quad (2.2)$$

Stress Range ($\Delta\sigma$)*:*
$$\Delta\sigma = \sigma_{max} - \sigma_{min} \quad (2.3)$$

Stress Amplitude (σ_a)*:*
$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \quad (2.4)$$

Stress Ratio (R)*:*
$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad (2.5)$$

2.3.5 S-N Curve

S-N curve refers to a plot of constant amplitude stress level (S) versus number of cycles to failure (N). S-N curves are generally plotted on semi-log or log-log paper where each dot represents the results of a single test specimen. The specimens will be tested until total failure and the cycle number N will be recorded and evaluated in respect to the corresponding load/stress level. Cycle numbers will be only considered during the analyses within a threshold of maximum two million cycles. The data is obtained by cycling smooth or notched specimens until failure. The usual procedure is

to test the first specimen at a high peak stress where failure is expected in a fairly short number of cycles. The test stress is decreased for each succeeding specimen until one or two specimens do not fail in the specified numbers of cycles, which is usually at least 10^7 cycles. The highest stress at which a run out (non-failure) occurs is taken as the fatigue threshold. Not all materials have a fatigue threshold (most nonferrous metallic alloys do not) and for these materials the test is usually terminated after about 10^8 or 5×10^8 cycles. Fatigue tests tend to be time consuming and expensive; each data point represents many hours of testing. A prediction of failure for various stress levels can be made by studying a material's S-N curve. The most important part of the curve is often the portion to the right of the bend or "knee" in the curve that identifies what is termed the endurance limit or the fatigue limit. The endurance limit is defined for material as the stress level below which the material can be cycled infinitely without failure. This is very important, because the result of exceeding this point most likely will be fatigue failure [32]. One typical S-N diagram is shown in Fig. 5.

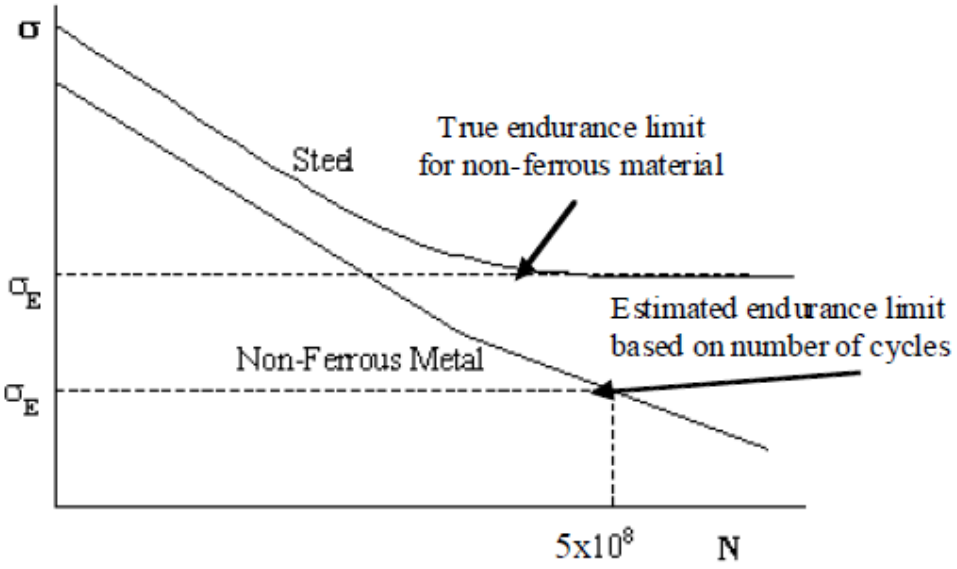

Fig. 5. S-N diagram showing endurance limits [32].

Basic fatigue testing involves the preparation of carefully polished test specimens, as surface flaws are stress concentrators.

2.4 Hardness

Hardness is the property of a material that enables to resist plastic deformation, penetration, indentation, and scratching, cutting or bending and measured by hardness tests. Hardness values can give information about the metallurgical changes caused by welding and galvanizing. Hardness measurements are widely used for the quality

control of materials because they are quick and considered to be nondestructive tests when the marks or indentations produced by the test are in low stress areas [35].

2.4.1 Hardness Test

Hardness test enables us to evaluate a material's properties, such as strength, ductility and wear resistance and helps to determine whether a material or material treatment is suitable for the required purpose. A hardness test is typically performed by pressing a specifically dimensioned and loaded object (indenter) into the surface of the material. The hardness is determined by measuring the depth of indenter penetration or by measuring the size of the impression left by an indenter. As per some researches and SEM investigations, zinc and zinc bath additives, which migrated to crack tips, are responsible for the loss in ductility. The phenomenon of LME is suggested to have taken place. In this phenomenon, the ductility of a solid metal drastically reduced after surface contact with liquid metals, which often have lower melting point and solidification temperatures than the solid metal. For investigating the presence of the phenomenon LME, it is necessary to check the hardness of base material in different areas to investigate the changes of ductility. Difference between hardness of galvanized steel and bare steel can show the presence of LME or diffusion of zinc bath additives [36, 41].

2.4.2 Hardness Test Methods

There are a large variety of methods used for determining the hardness of a substance. Two principal methods of testing the hardness of a material are scratch testing and indentation testing. Indentation testing can only be used on materials that undergo plastic deformation such as metals and thermoplastic polymers. Scratch testing is therefore used for brittle materials such as ceramics [36].

- **Scratch Testing**

The hardness of a material can be determined based on Moh's scale of hardness, which ranks a material based on a list of standard materials with known hardness. The hardness of the material is ranked on the scale between the material just scratches and the material that fails to scratch [36].

- **Indentation Testing**

There are a number of different methods of testing the hardness of a material through indentation. The three most commonly used are the Brinell test, the Vicker's

Diamond test, and the Rockwell test. All three methods involve indentation of the material. These methods are shown in Fig. 6. The hardness is calculated by measuring the force applied and comparing this to some geometrical aspect of the indentation such as the surface area or depth. When hardness indentation testing is done on an actual component, it is often necessary to blend (grind) out the indentation to remove the stress concentration it produces [36, 41].

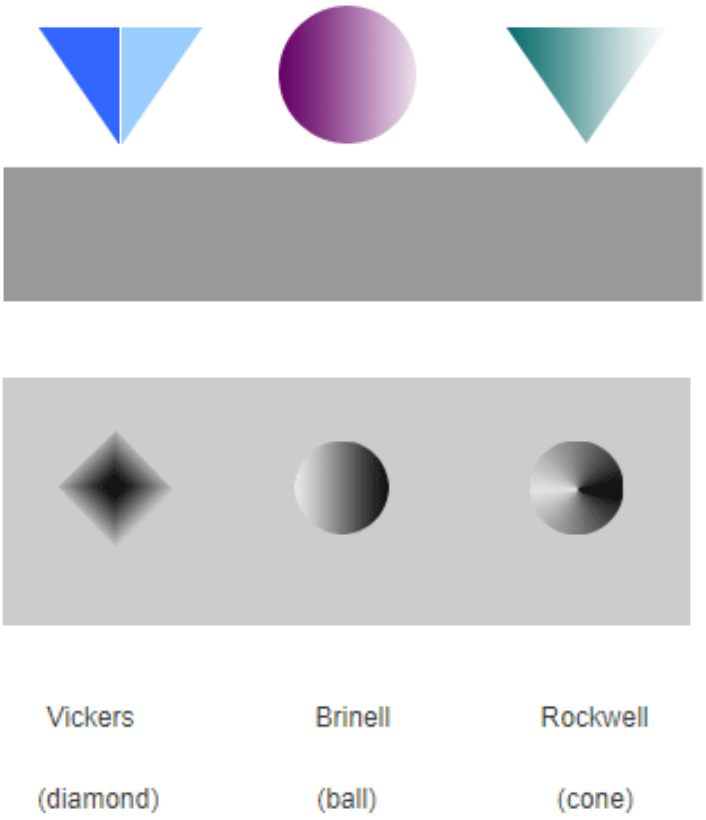

Fig. 6. Different hardness test methods [36].

2.4.3 Different Hardness Tests

Resistance of a material to deformation, indentation or penetration by means such as abrasion, drilling, impact, scratching, and wear, measured by hardness tests such as Brinell, Knoop, Rockwell, or Vickers and Mohs' hardness scale. The three most commonly used hardness tests are the Brinell test, the Vicker's Diamond test, and the Rockwell test. The hardness is calculated by measuring the force applied and

comparing this to some geometrical aspect of the indentation such as the surface area or depth [37].

- **Brinell Hardness Test**

Today, the oldest method of hardness test in common use on engineering materials is Brinell hardness test. The Brinell test uses a desktop machine to applying a specified load (P) to a hardened sphere of a specified diameter. The Brinell test uses a hardened steel ball indenter with a diameter of 10 mm. The indenter is applied to the test material under a load of 3000 kg. The surface area of the indentation is then measured to derive the hardness, HB of the material.

$$HB = \frac{applied\ load\ (kg)}{surface\ area\ of\ the\ impression\ (mm^2)} \tag{2.6}$$

The Brinell hardness number (BHN) is the load in kilogram divided by the surface area of the indentation in square millimeter. The diameter of the impression is measured with a microscope with a superimposed scale. HB is computed from the equation: P is the applied load of 3000, 1500, or 500 kg. A value reported as "60 HB 10/1500/30" means that a Brinell hardness of 60 was obtained using a 10 mm diameter ball with a 1500 kilogram load applied for 30 seconds. A wide range of materials can be tested using a Brinell test simply by varying the test load and indenter ball size [37].

- **Vicker's Diamond Test**

The Vickers Hardness (VH) test is a modification of the Brinell test and is used to measure the hardness of thin film coatings or the surface hardness of case-hardened parts. With these tests, a small diamond pyramid is pressed into the sample under loads that are much less than those used in the Brinell test. The Vickers test uses a square pyramidal shaped diamond indenter with an apex angle of 120° which is prone to crack brittle materials. The use of diamond as an indenter means that very hard materials can be tested as they are not likely to deform the indenter. The force, F, is taken and the diagonals of the impression are measured. The mean of these two values, D, is used to determine the hardness, VH, of the material [37].

An applied load ranging from 10 g to 1,000 g is used. This low amount of load creates a small indent that must be measured under a microscope. The measurements for hard coatings like TiN must be taken at very high magnification (i.e. 1000X), because the indents are so small. The surface usually needs to be polished. The diagonals of the impression are measured, and these values are used to obtain a Vickers hardness number (VHN), usually from a lookup table or chart. The Vickers

test can be used to characterize very hard materials but the hardness is measured over a very small region. The VHN is calculated by optically measuring the diagonal lengths of the impression left by the indenter. The measurements are converted to *HV* using a table or formula. The values are expressed like 2500 *HV* 25 meaning 2500 Hardness Vickers at 25 gram force load [37].

$$HV = \frac{1.8544\,F}{D^2} \quad [Kgf/mm^2] \tag{2.7}$$

- **Rockwell Test**

The Rockwell test is designed as a method of hardness testing for rapid comparative analysis. The Rockwell Hardness test also uses a machine to apply a specific load and then measures the depth of the resulting impression. The indenter may either be a steel ball of some specified diameter or a spherical diamond-tipped cone of 120° angle and 0.2 mm tip radius, called a brale. For soft materials such as copper alloys, soft steel, and aluminum alloys a 1/16 inch diameter steel ball is used with a 100-kilogram load. In testing harder materials, hard cast iron and many steel alloys, a 120 degrees diamond cone is used with up to a 150 kilogram load. The depth of the impressions are measured and rated on a dial calibrated, inversely, into 100 divisions. A deep impression will result in a low value, which implies a soft material. Hardness Rockwell (HR) is hardness number. Hardened steel ball indenters are used with diameters of 1/16 inch, 1/8 inch, 1/4 inch, and 1/2 inch. Standard indenting loads are 60kg, 100kg and 150kg [37, 41].

2.4.4 Surface Preparation for Hardness Test

Before placing the sample material in the micro hardness testing machine, we should ensure it is correctly prepared. The required surface condition for the Vickers hardness test depends on the load used [37, 41].
For macro hardness testing (loads higher than 1 kgf):

- Surface should be ground.
- Surface should be mechanically polished or electro polished.
- Indentation time should be 10-15 seconds.
- Sample thickness should be at least 10 times the indentation depth (ASTM).
- Sample thickness should be at least 1.5 times the diagonal length (ISO).

2.5 Metallography

Metallography is the study of the physical structure and components of metals, typically using microscopy test. The surface of a metallographic specimen is prepared by various methods of grinding, polishing and etching. After surface preparation, it is often analyzed using optical microscopic test or SEM test. Mechanical preparation is the most common preparation method. Successively finer abrasive particles are used to remove material from the sample surface until the desired surface quality is achieved. Many different machines are available for doing this grinding and polishing, which are able to meet different demands for quality and capacity. Chemical or other etching methods are often used to delineate macrostructure and microstructure features. Once prepared, samples are examined by the unaided eye, light microscopy and SEM. For microstructure examination, a mirror finish is needed, but a fine-ground finish is adequate for macrostructure evaluation [38].

2.6 Microstructural Characterization Methods

2.6.1 Optical Microscopy

An optical microscope uses one or a series of lenses to magnify images of small samples with visible light. These lenses are placed between the sample and the viewer's eye to magnify the image so it can be examined in greater detail. The fracture investigation and microstructural analysis of the parent and galvanized S_{355} steel structures have been done by using an optical microscope. By optical microscope the presence of cracks can be identified.

2.6.2 SEM Test

- **SEM Principles and Capacities**

SEM analysis is a non-destructive test, that is, x-ray generated by electron interactions do not lead to volume loss of sample, so it is possible to analyze the same materials repeatedly. SEM is a type of electron microscope that produces images of a sample by scanning the surface with a focused beam of high-energy electrons generates a variety of signals at the surface of solid specimens. The electrons interact with atoms in the sample, producing various signals that contain information about the sample's surface topography, chemical composition and crystalline structure and orientation of materials making up the sample. The electron beam is scanned in a raster scan pattern, and the beam's position is combined with the detected signal to produce an image [38, 42].

SEM can produce very high-resolution images of a sample surface, revealing details less than one nanometer in size. SEM analysis shows if there is any pre-existing crack and it shows crack propagation from zinc layer to steel also hydrogen embrittlement and LME can be identified by SEM. One SEM micrograph is shown in Fig. 7. In Fig. 8, SEM test shows the zinc soaked into the steel and crack initiation [2].

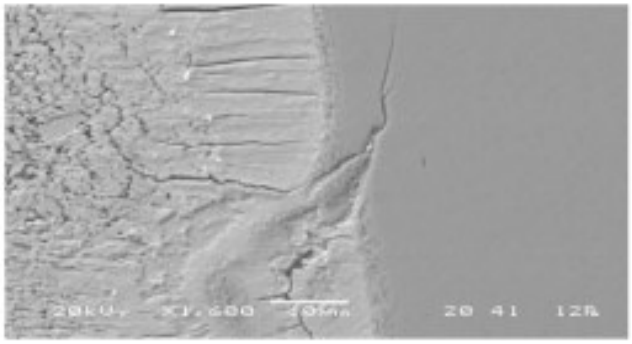

Fig. 7. SEM micrograph of the galvanized steel after fatigue [2].

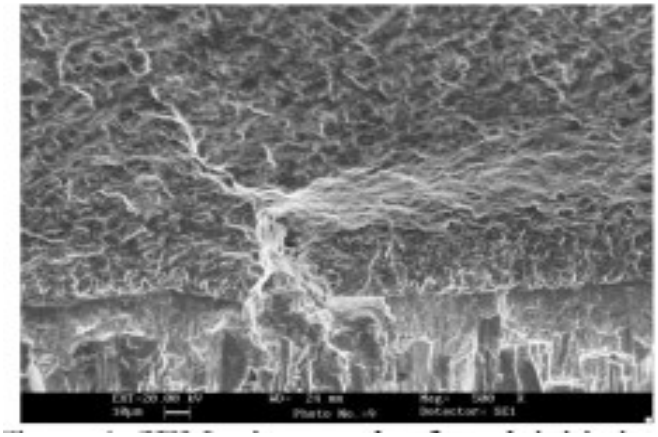

Fig. 8. SEM micrograph of crack initiation [2].

- **SEM Applications**

The SEM used to generate high-resolution images of shapes of objects and to show special variations in chemical compositions utilizing:

1) Acquiring elemental maps or spot chemical analysis using energy dispersive spectroscopy (EDS).

2) Discrimination of phases based on mean atomic number (commonly related to relative density) using backscattered electron images (BSE).
3) Compositional maps based on differences in trace element "activators" (typically transition metal and rare earth elements) using cathodoluminescence (CL) [38].

- **SEM Sample Preparation**

Proper sample preparation plays an important role in obtaining the required information when using SEM. You need to consider the sample's size, shape, state, and conductive properties prior to sample preparation. Samples for SEM have to be prepared to withstand the vacuum conditions and high-energy beam of electrons and have to be of a size that will fit on the specimen stage.

For conventional imaging in the SEM, specimens must be electrically conductive, at least at the surface, and electrically grounded to prevent the accumulation of electrostatic charge. A clean sample is necessary for image clarity. For samples use distilled water for cleaning the samples. To remove oils on the sample surface, wash with appropriate solvents. Prior to placing the sample in high vacuum environment, it must be totally dry. Otherwise, water vaporization will obstruct the electron beam and interfere with image clarity [38, 42].

3. Experimental Research Methods

3.1 Introduction

The aim of the experimental works is to investigate the effect of hot- dip galvanized fillet welded cruciform joints on the fatigue strength compared to the uncoated specimens and also study the fracture surface of galvanized and non-galvanized specimens. For investigating effect of HDG on fatigue of S_{355}, different tests have been conducted on the specimens. These tests have been presented in the following sub-chapters. Fatigue tests have been conducted on the specimens to investigate the effect of HDG on fatigue strength of S_{355}. Fatigue tests were carried out in room temperature and in the atmosphere. The fatigue strength of the material in the presence of the zinc layer has been studied.

Sixteen specimens have been welded (fillet weld) and ten series (specimen No. 1-10) of the sixteen specimens have been later hot dip galvanized. Fourteen specimens were tested out of sixteen (ten coated and four non-coated ones). In the fatigue test, the test specimens have been subjected to dynamic loads with a constant range. A sinusoidal load cycle and stress range ratio of R= 0.01 have been considered for this study. The fracture surfaces of all broken specimens have been studied macroscopically and four specimens have been tested microscopically in order to highlight crack initiation site using microscopic test and SEM analysis. Hardness test has accomplished to check the ductility of the base metal, HAZ and weld to investigate LME phenomenon.

3.2 Parent Material and Weld Properties

One type of parent material normal steel S_{355} for the tests have been used with two types of surface finish with and without a corrosive protective galvanized layer. The fatigue tests have been carried out on S_{355} specimens. Load carrying on the fillet welded cruciform joints, which have been welded by means of automatic MAG technique. Later, ten series of the sixteen specimens have been hot dip galvanized.

3.2.1 Chemical Composition of Base Material

The testing was carried out on specimens of S_{355} steel, whose chemical composition is presented in the Table 1.

Table 1. Chemical Composition of S355 steel.

C%	Si%	Mn%	Cr%	Ni%	S%	P%
0.2	0.55	1.6	0.003	0.003	0.025	0.025

3.2.2 Geometry of Test Specimen

The steel plates used to fabricate the samples were 10 mm in thickness, while the specimen had a global length of 250 mm. The weld throat, a can be calculated, as $a = \left(\frac{\sqrt{2}}{2}\ 8\ \text{mm}\right) = 5.65\ \text{mm}$. The configuration of the specimen is shown in Fig. 9.

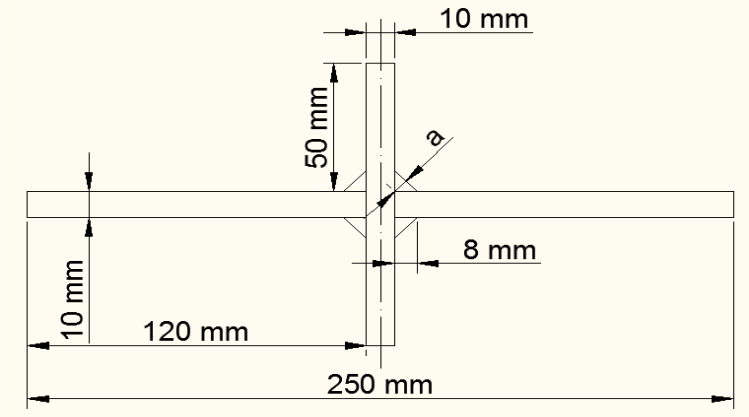

Fig. 9. Geometry of the fillet welded specimen.

3.2.3 Hot-Dip Galvanization

Hot-Dip galvanization takes place in two steps. Firstly, steel part surface is prepared with pretreatment bath: degreasing, pickling, rinsing, fluxing and drying. The steel to be coated is firstly cleaned to remove all oils, greases, soils, mill scale and rust. Cleaning usually consists in a degreasing step followed by acid pickling, in order to remove scale and rust, and by fluxing, in order to apply a protective surface and inhibit the steel oxidation before dipping in molten zinc.

Secondly, it is dipped in molten zinc bath for galvanization. HDG main parameters are bath composition, temperature and treatment time. Regarding the galvanized series, the coating treatment has been carried out at a bath temperature of 452℃ and the immersion time was kept equal to 6-8 min and immersion velocity of 1.5 m/min for all the specimens. As a consequence of the bathing temperature and immersion time, the coating thickness resulted in a range between 470 and 500 μm.

3.2.4 Chemical Composition of the Zinc Bath

Chemical composition of zinc bath has been presented in Table 2.

Table 2. Chemical Composition of Zinc Bath.

Al%	**Cu%**	**Pb%**	**Sn%**	**Cd%**	**Fe%**	**Mg%**	**Mn%**
0.0031	0.017	0.0067	0.0065	0.0003	0.0183	0	0.0016
Ni%	**Sb%**	**Ti %**	**As%**	**Bi%**	**Cr%**	**Zn%**	**–**
0.0381	0.0024	0.0003	0.0009	0.0837	0.0012	99.82	–

3.3 Fatigue Test

Fatigue test was performed to determine steel fatigue behavior and properties after HDG. The testing equipment is a servo hydraulic machine MTS 647. The tests were performed on both bare and hot-dip galvanized samples. All tests were carried out at room temperature.

The welded joints were tested by using a cyclic axial tension loading with load ratio R=0.01, however for each test run the minimum load value was set to 1 kN due to limitation of the force measure and test arrangement. The fatigue tests were force controlled and load amplitude was kept constant for each test specimen. The load frequency was ranging between 10 and 15 Hz. The first experiment was conducted at 15 Hz until total failure, whereas the following experiments were performed at a high frequency of 10 Hz initially and stopped when the axial displacement reached 1.5 mm, following the test was continued at a lower frequency of 2 Hz for the last couple of cycles until total failure. Figure 10 shows the test arrangement and used servo hydraulic machine MTS 647, where the end of the test specimens were mechanically attached to the clamp-system. The clamp-system was rigid without hinge as usually in this kind of material testing system [39].

Fig. 10. Fatigue test equipment [39].

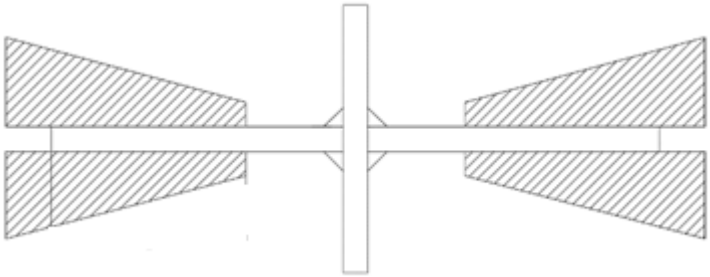

Fig. 11. Picture of direction of loading on the welded joints [39].

Figure 11 shows the direction of loading on the welded joints [39]. The fatigue strength of galvanized and non-galvanized cruciform fillet joints was investigated in order to determine the differences in fatigue strength between the coated and non-coated materials. During the tests all-together fourteen specimens were tested, which ten were galvanized and four were non-galvanized.

The specimens' ends were machined to lower the secondary bending stresses before clamping on the machine. The load level was selected and applied on the specimens as well as the stress range calculated based on the load, parent material geometry and the stress ratio, the range of loads is between 77 and 187 MPa. Tests were run until total failure or reaching two million cycles. One broken sample after fatigue test is shown in Fig. 12.

Fig. 12. Typical broken specimens under fatigue test [39].

3.4 Hardness Test

In this thesis, we used Vickers hardness test as Vickers hardness test is suitable for a wide range of applications, including micro hardness testing. Vickers hardness test is often easier than other hardness tests to use [36].

Standard steel samples were made through cutting and polishing for hardness tests. We used the Vickers hardness method with 300 (gf) and the time of loading 10 s for three specimens. Hardness of specimens has been checked in HAZ area, weld area, base material very close to galvanized coating. Three types of specimens have been checked.

1. Galvanized broken from weld toe (specimen N0. 1).
2. Galvanized unbroken (specimen No. 10).
3. Non galvanized and broken from weld toe (specimen No. 20).

Specimens No. 20, which is non-galvanized and broken specimen from weld toe, is shown in Fig. 13. The hardness test area has been marked on the picture.

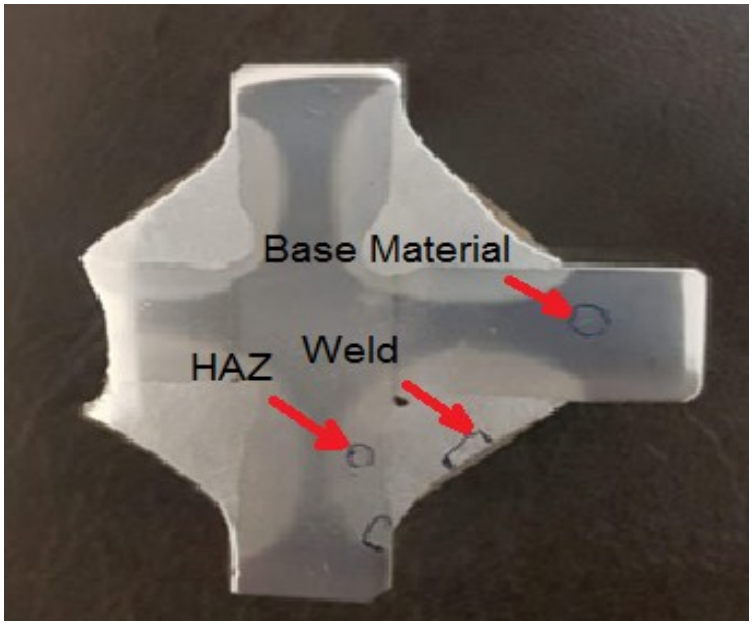

Fig. 13. Hardness test points of specimen No. 20 after etching.

3.5 Microstructural Tests

The following tests have been carried out on the specimens to find out connection between cracking in the coating and cracking in the steel substrate. Micrographic observations of fracture surface from welded hot dip galvanized S_{355} structural steel after fatigue test.

1. Optical microscopy of galvanized coating and steel substrate after fatigue test.
2. SEM test.

SEM test equipment is shown in Fig. 14.

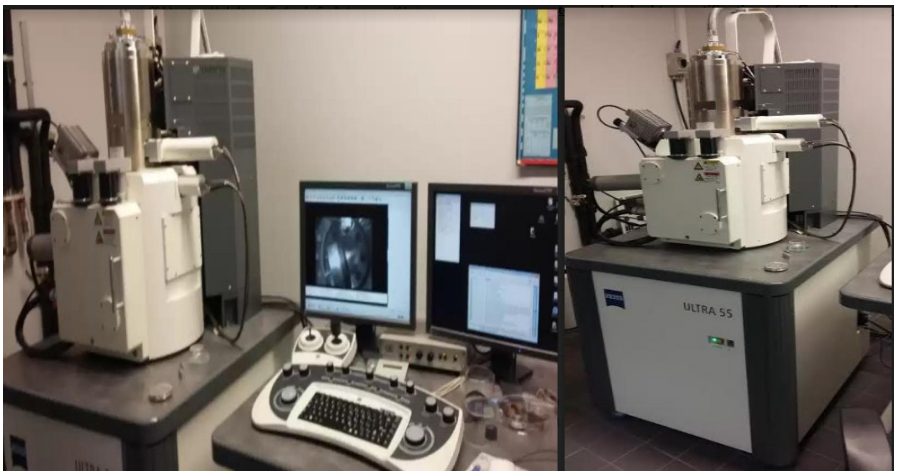

Fig. 14. SEM test equipment.

Fractured and polished samples have been studied with an optical microscope. Etching by Nital 2% has been done for checking the coating condition in different area. Metallurgical microscope was used to investigate the microstructural features of the specimens before and after failure in fatigue test in different magnifications. To fallow analysis of fatigue failure, various micrographs were produced.

For investigating of HDG effect on the fatigue strength after fatigue test, the specimens, which have been broken from the weld root, were ignored. We studied the specimens broken from the weld toe or specimens, which have not been broken. In this regard, we selected below specimens.

1. Specimen No. 5, galvanized and broken from weld toe.
2. Specimen No. 10, galvanized and non-broken.
3. Specimen No. 1, galvanized and broken from weld toe.
4. Specimen No. 20, non-galvanized and broken from weld roots and weld toe.

Two pieces of samples were studied in SEM test. First sample is one piece of sample No. 5 that is a galvanized and broken. Another sample is the specimen No.10, which is galvanized and non-broken sample. Specimen No. 10 is galvanized and non-broken specimen, test stopped in 2,000,000 cycles. For the specimen No. 10 cutting, grinding, polishing and etching with Nital 2% were done and the galvanized surface of the specimen was investigated optically and under the microscopic tests. The equipment for cutting specimens is shown in Fig. 15. Figure 16, depicts grinded, polished and etched specimen No.10 under SEM test.

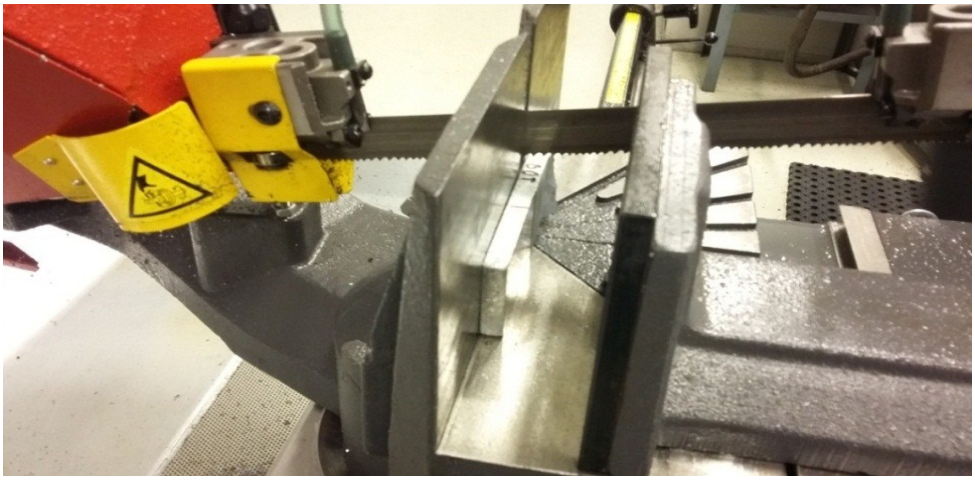

Fig. 15. Cutting specimens No. 10 done by water jet.

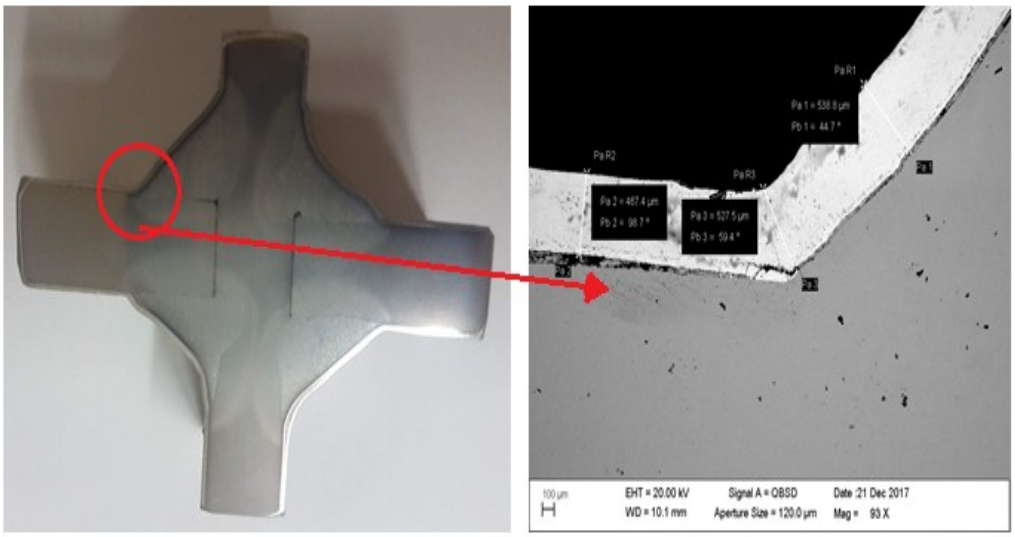

Fig. 16. Grinded and etched specimen No. 10 under SEM test

4. Experimental Results and Discussion

4.1 Fatigue Test Results

Fatigue tests were conducted by using a servo hydraulic machine MTS 647 test system for fourteen specimens, ten galvanized and four bare specimens. The data for fatigue test strength were recorded based on the number of cycles and the nominal stress range (considering the minimum and maximum applied load) and results are presented in Table.3.

Table. 3 Fatigue Test Result Values [39].

No.	Type	Δσ_nom MPa	N cycles	Note
Spec_1	Galvanized	187	89031	
Spec_2	Galvanized	145	180038	
Spec_3	Galvanized	130	353732	
Spec_4	Galvanized	147	284514	
Spec_5	Galvanized	105	1013680	
Spec_6	Galvanized	0	0	
Spec_7	Galvanized	0	0	
Spec_8	Galvanized	99	859439	
Spec_9	Galvanized	168	197183	
Spec_10*	Galvanized	~~85~~	~~2000000~~	Run-out test
Spec_11	Galvanized	116	820987	
Spec_20	Non-Galvanized	170	171010	
Spec_21*	Non-Galvanized	~~77~~	~~2909530~~	Run-out test
Spec_22	Non-Galvanized	119	745003	
Spec_23	Non-Galvanized	95	983684	
Spec_24	Non-Galvanized	120	716488	

* Specimens were run out and tests were stopped no crack initiation noticed

Two of the specimens have not been broken; these specimens are specimen No. 10 under load 85 MPa and specimen No. 21 under load 77 MPa. Based on the minimum and maximum values as well as the geometry of the specimen, the actual stress range was calculated ($\Delta\sigma = \sigma_{max} - \sigma_{min}$) and plotted in terms of the cycle number in log-log, S-N curve for galvanized and bare steel as shown in Fig. 17. The tests were run for both types of specimens at load levels varied between 32 kN and 80 kN (77 and 187 MPa), respectively in order to estimate the S-N curve [39]. As per S-N graph is shown in Fig. 17, fatigue strength in low cycles does not have a big difference for bare and galvanized steel.

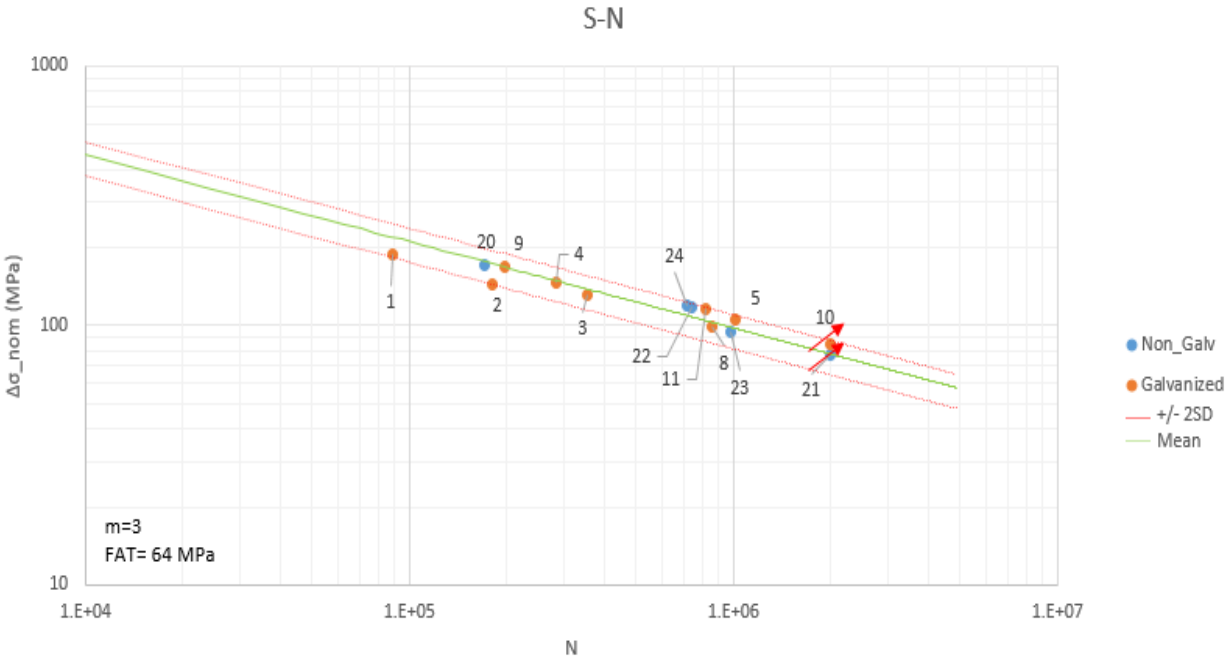

Fig. 17. S-N curve of test specimens with mean value of all data points [39].

The fatigue test results and graphs show that there is not big difference in fatigue strength between bare and galvanized specimens in low cycle area. The analysis of failed steel structures has shown some common features. After the fatigue tests, the specimens were examined and fracture surfaces were analyzed to get information about the crack initiation and propagation. During tests, singular or simultaneous crack initiation started mainly on the root side of the fillet welds and propagation happened through the weld throat, but in some cases also secondary and tertiary crack initiation happened on the toe side, as well.

Nevertheless accounting for the coating parameters i.e. thickness as well as removing the coating layer from the parent material might give different results in terms of fatigue strength. From Figure 17, it can be seen that galvanized specimen No.2 and specimen No. 1 fail sooner than expected. These fillet joints might require further analysis and discussion.

4.2 Hardness Test Results

As hydrogen embrittlement and zinc diffusion can be reasons for fatigue strength reduction and these phenomena can affect the ductility and hardness, we checked the hardness of material for three specimens. We used the Vickers hardness method with 300 (gf) and the time of loading 10 s for three specimens. Specimen No. 1, No. 10 and No. 20 in three different areas and for each area the test has been done three times. The results of the hardness for three specimens are presented in Table 4.

Table. 4 Hardness Test Results**.**

Test Method Specification				
Time (s)	**Force (gf)**	**Method**		
10	300	Vickers		
Hardness Test Results (HV)				
Specimen No.1 (Galvanized Broken Specimen)				
Test No.	**1**	**2**	**3**	**Average Hardness**
HAZ Area	132	141	142	138
Welding Area	130	110	122	121
Based Material	100	97	105	101
Specimen No.10 (Galvanized Unbroken Specimen)				
Test No.	**1**	**2**	**3**	**Average Hardness**
HAZ Area	220	210	203	211
Welding Area	204	207	213	208
Based Material	187	185	192	188
Specimen No.20 (Non-galvanized Broken Specimen)				
Test No.	**1**	**2**	**3**	**Average Hardness**
HAZ Area	218	210	214	214
Welding Area	200	209	213	207
Based Material	179	177	187	181

During hardness test of the specimen No. 1 which is unbroken and galvanized, we found that the microstructure of material is not similar to those related to specimens No. 10 and No. 20. It means that material of the specimen No. 1 is not S_{355} and it can be S_{235}.

By comparing hardness test result in three points, base material, HAZ and welding area, the result of hardness test shows that galvanizing does not have a big effect on hardness of material. The results show that the hardness is identical at these three different areas. It means that galvanizing has not affected the base material's hardness. As hardness is related to ductility, it reveals that ductility has not been changed by galvanizing. We know that in LME phenomenon, ductility of material will be changed by migrating of zinc bath additives to crack tips. As hardness result shows that hardness has not been changed after galvanizing, we can conclude that zinc diffusion and LME have not happened in the base steel during galvanizing process.

4.3 Macro Observation, Micro Optical Test and SEM Results

For more investigation, the failed specimens from the weld toe and samples of non-broken specimens were selected to find out the effect of HDG on their microstructures. Results of microstructure test of specimens No. 5, No. 10, No. 20 and No. 1 have been presented in the section below.

Specimen No. 5:

The fracture surface of the specimen No. 5 that failed from weld toe during fatigue test has been checked to find crack initiation area. Figure 18 shows crack propagation and the coating condition after fracture. Initial crack marked on the picture and shows propagation from backside top weld toe.

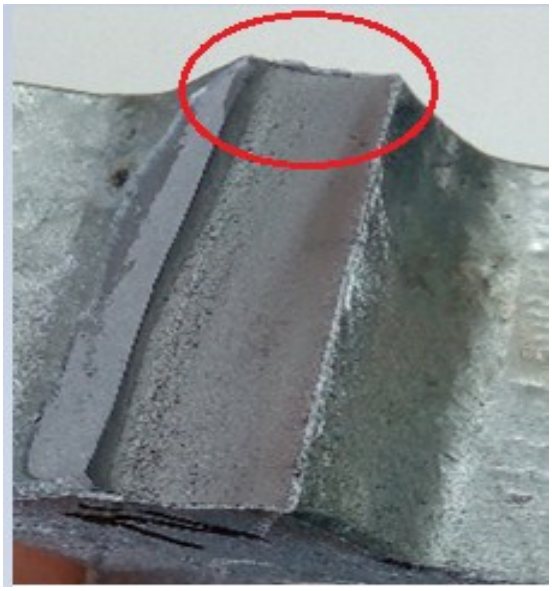

Fig. 18. Specimen No. 5, macro observation of fracture surface after cyclic loading.

Debonding and delamination are two possible reasons that can affect fatigue strength. It should be noted that when the coating thickness exceeds about 200 microns, the thick alloy layers become more prone to delamination. The thermal stresses generated by this differential heating or cooling cause high shear forces at the steel/coating interface. Shear stress induced by thermal stress during cooling after galvanizing can lead to the formation of tangential cracks and this can cause separation and arising coating from the substrate. In-sufficient adhesion and delamination cannot resist against fatigue load and reduces fatigue strength [40].

After welding, stress concentration in the weld toe area is increased. Using galvanizing creates a layer that induces smooth coating with big curvature. Although it can reduce stress concentration in the weld toe and increases the fatigue strength, coating has been debonded from the steel substrate since it is under fatigue test and axial loading. Thus, there is a separation between galvanizing and the base material. This cavity, in turn, can act as a severe stress concentration. Debonding can cause holes between the galvanized material and base metal, which is the cause of stress concentration, leading to the formation and propagation of cracks.

In this thesis debonding and delamination have been observed. Macro graphic figures show weak interconnection between Zn and steel substrate that probably depends on HDG bath condition (temperature and composition) and the quality of cleaning the surface before HDG. Moreover, there is some segregation between coating and steel substrate in some locations after fatigue test. As we can observe in Fig. 19, debonding has been created between HDG and base metal after cyclic loading in some locations. By this segregation, debonding can happen and it means that many holes have been appeared between coating and base material. These holes are the location of stress concentration and can be the crack initiation site.

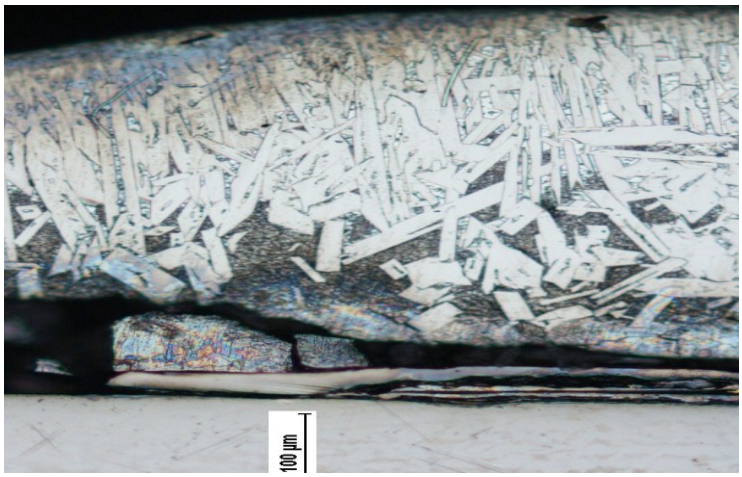

Fig. 19. Debonding between the base material and coating.

Figures 20 and 21 show debonding at interface of the base metal and coating, which leads to stress concentration and crack initiation at fracture surface of the specimen No. 5.

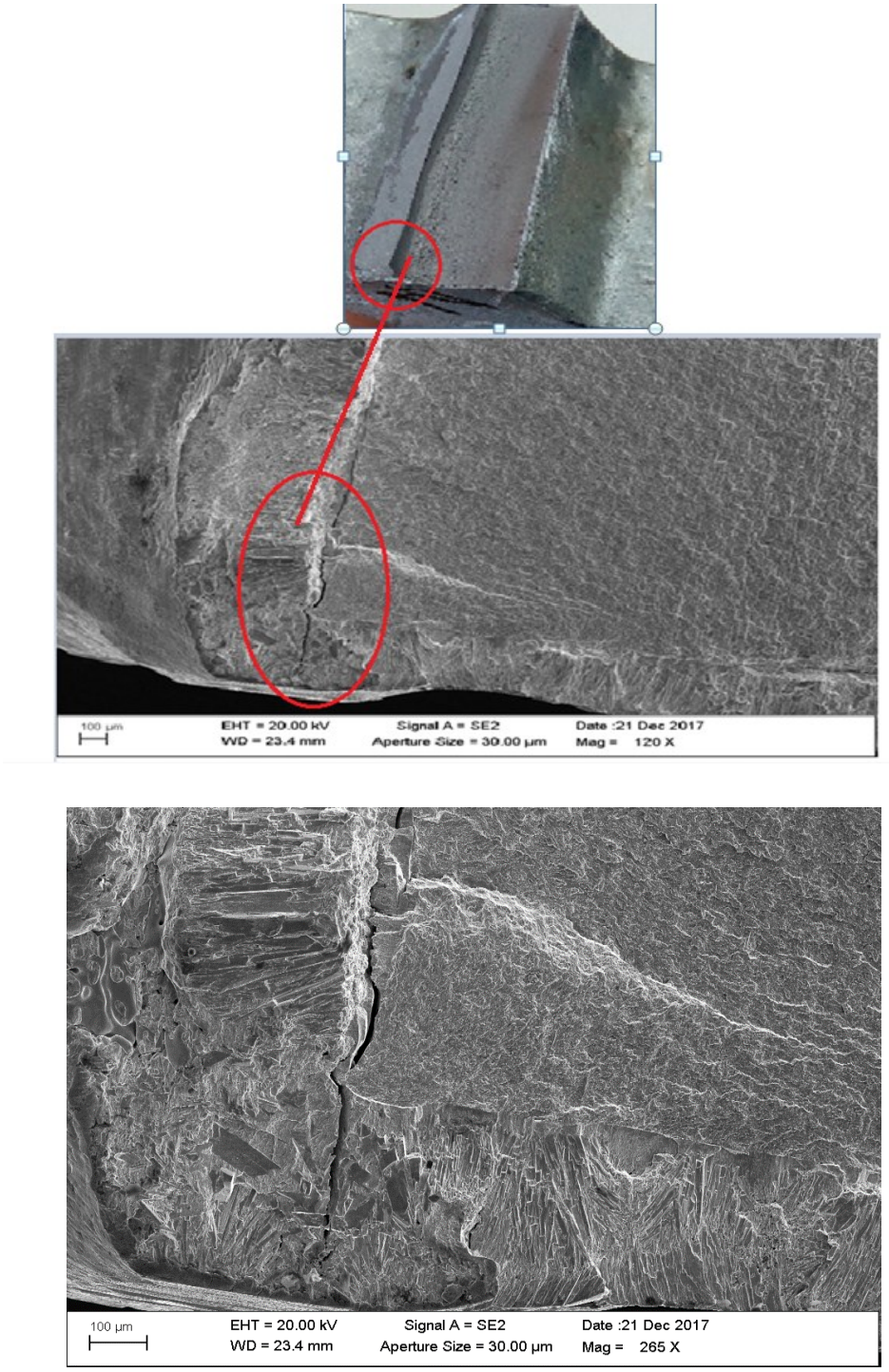

Fig. 20. Specimen No. 5, de-bonding between substrate and coating observed by SEM.

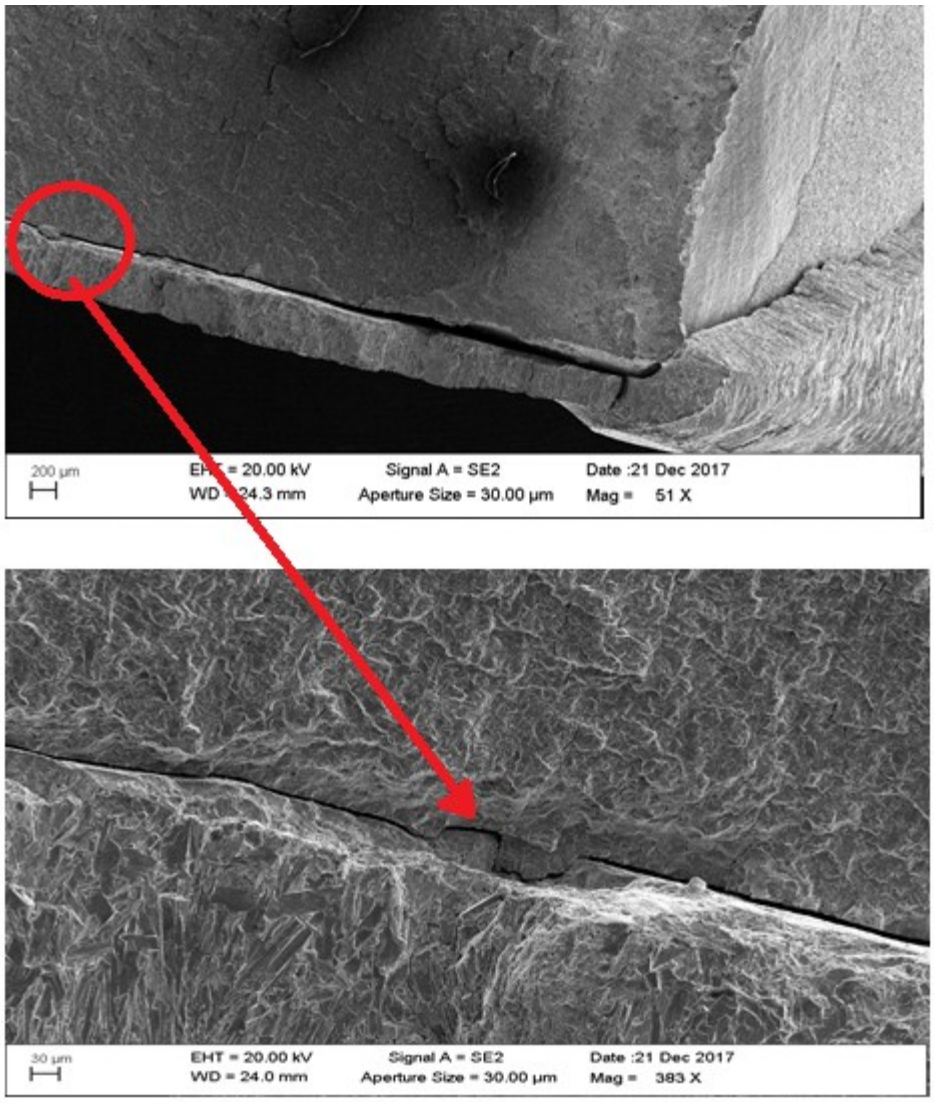

Fig. 21. Specimen No. 5, de-bonding in fracture surface.

Specimen No. 10

After fatigue test, specimen No. 10 has been cut by water jet and has been grounded, polished, and investigated from the view point of microstructure of the material in the HAZ area and galvanized part. In microstructure tests, defects were observed at the welding root. These defects can be a location for crack initiation. Some cracks are observed around the weld root, which make weak points in the base material. As many specimens have been broken from the root, we should consider these weak points as a site for crack initiation.

In Fig. 22, it can be observed that the quality of the weld is very poor. Two thin black lines in the middle of the specimen depict non-welded area between fillet welds. Moreover, it can be seen that there is lack of penetration. As we have fillet weld and

there is not complete diffusion, it can cause stress concentration, which is suspend to crack initiation. It means this defect makes shorter time for crack initiation. When there are these types of defects in welding, it is not clear that the fracture has been happened by weak welding points or galvanizing of the specimens. In order to achieve more accurate results, welding should be conducted based on welding procedure specification (WPS) and specimens with sound weld and without defects should be selected as samples for fatigue test. Samples of incomplete diffusion welds in the welding area of the specimen No. 10 are shown in the following figures.

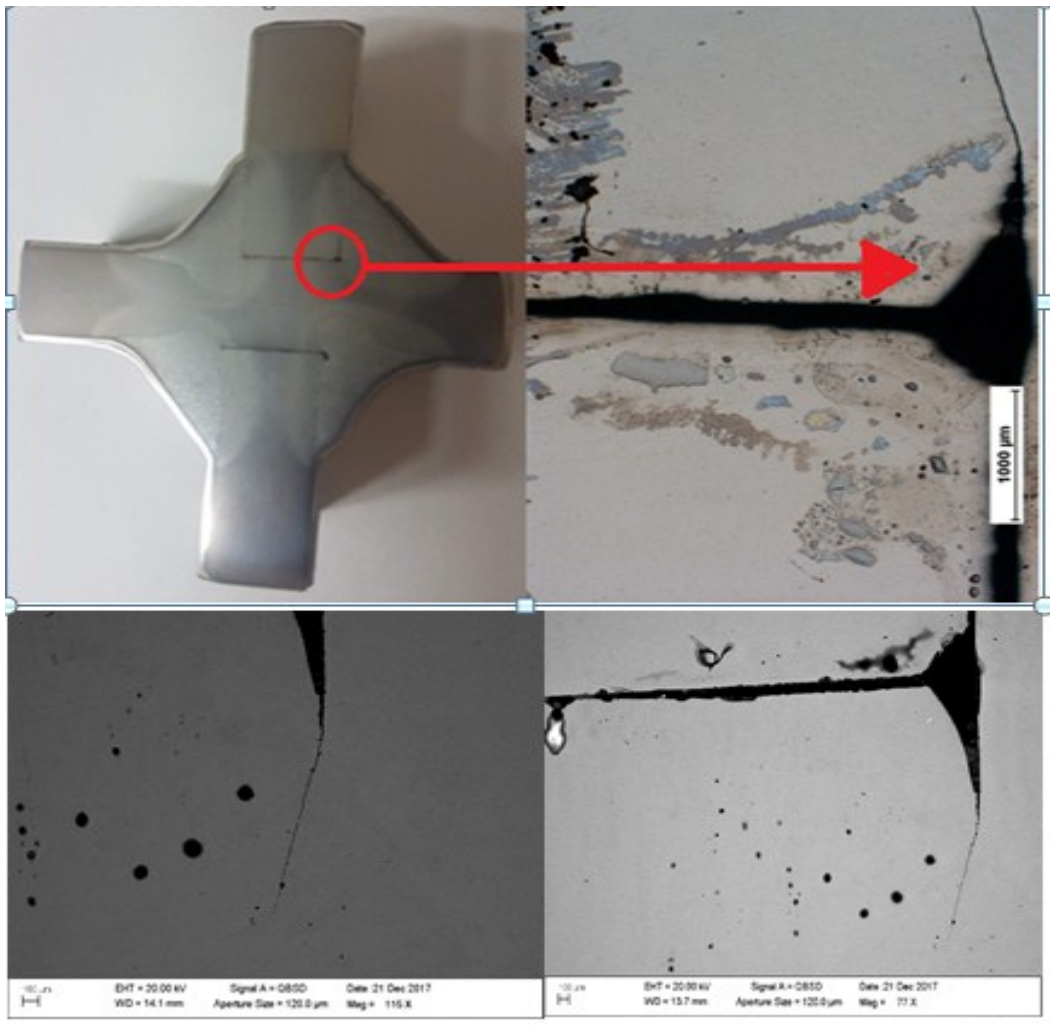

Fig. 22. Specimen No. 10, macro and micro observation after polishing and etching.

In Figs. 22 and 23, different weld area and HAZ can be observed. First, it may be revealed that the quality of the weld is very poor. At the section, there is lack of penetration, poor root formation and incomplete welding which is the site of crack initiation.

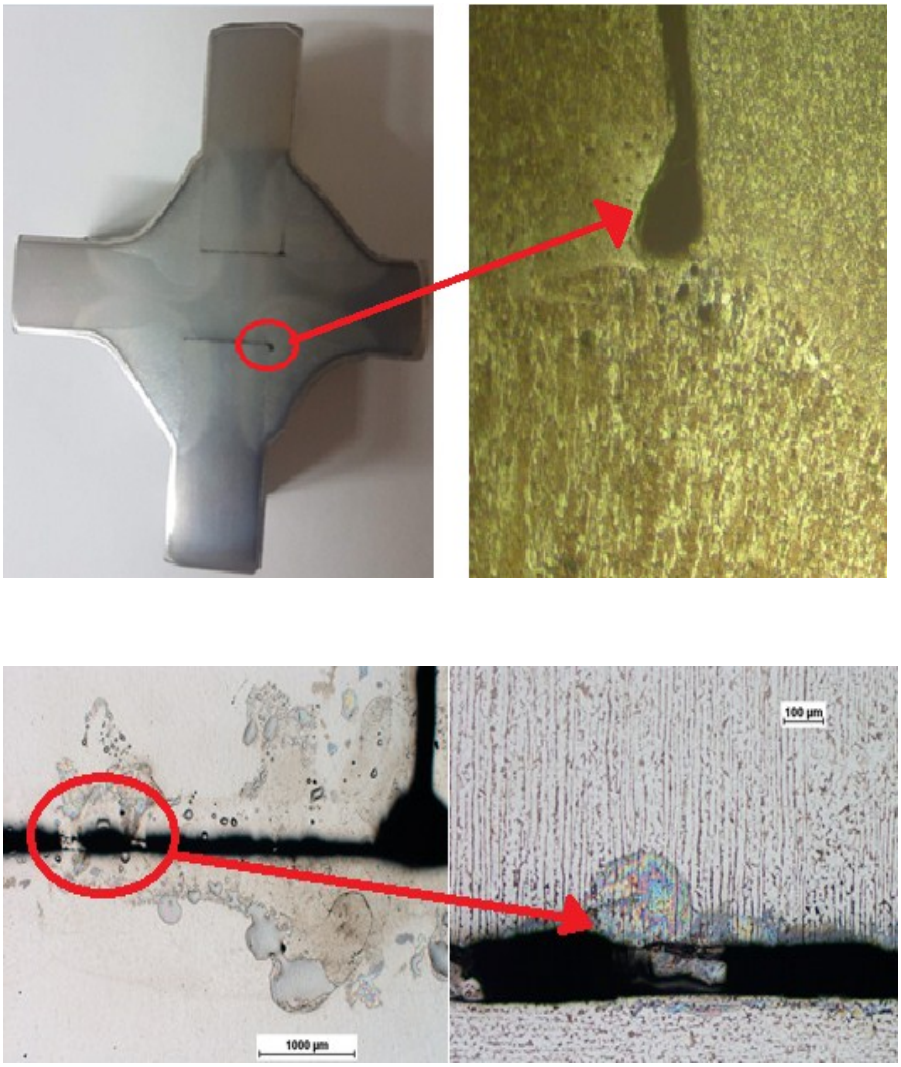

Fig. 23. Crack initiation in the welding area specimen No. 10 at weld root.

Figure 24 shows the microscopic structures of galvanizing area of the specimen No. 10. This figure depicts that notch has been created in galvanized coating close to weld toe. In microstructural test, we observed notches and cracks in coating layer. In some areas close to weld toe, notches and deep cracks were observed. In our experimental observations, we found two deep cracks in coating layer around the welded toe area. These cracks are shown in Fig. 24 and Fig. 25.

Based on our results from microscopic tests, we can conclude that although in some areas, cracks have been stopped in interface of galvanized and base material, but cracks have ability to propagate to the base material when they cross the whole thickness of coating. In the weld toe area, some of these cracks have been passed through the interface between galvanized and base material and have been diffused to the base material.

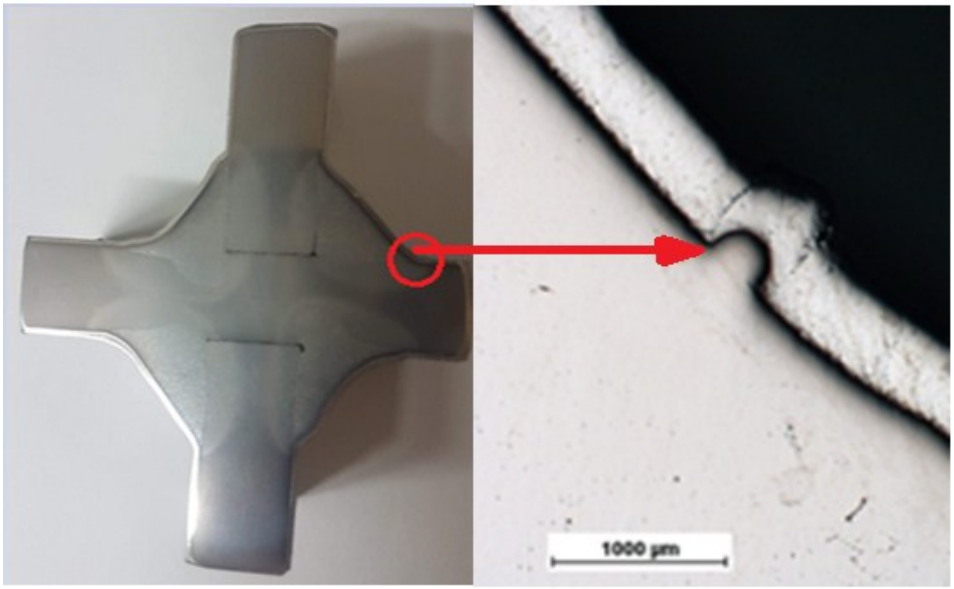

Fig. 24. Specimen No. 10, with notch close to weld toe.

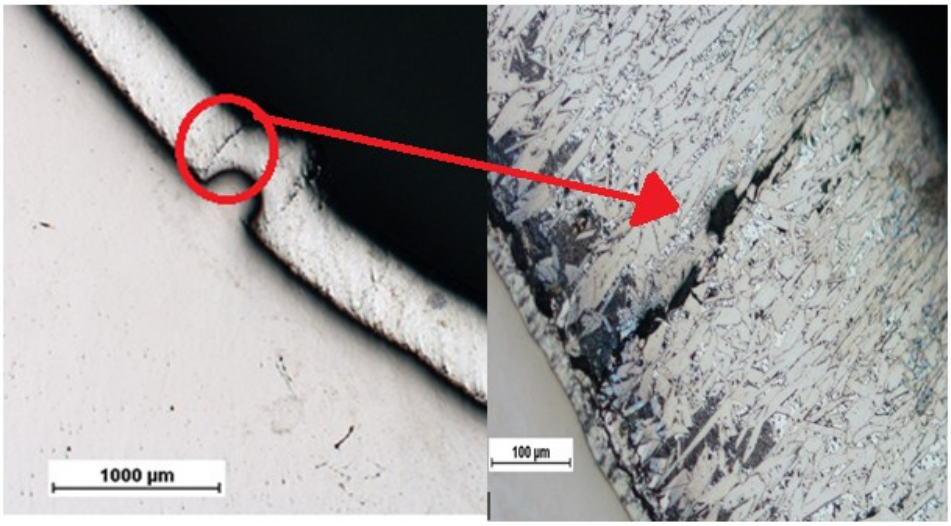

Fig. 25. Specimen No. 10, deep crack in notch area close to weld toe.

Figure 25 shows propagation of deep crack into coating which is originated from the corner of the notch. It reveals that crack has been stopped in the interface of steel substrate and galvanized coating. We should consider whether this deep crack could be propagated to the steel substrate under cyclic loads. The crack was found to be approximately 500 µm as illustrated in the figure. Induced micro cracks in the galvanized coating after fatigue loading can be another reason for crack initiation and crack propagation to base metal. These cracks can be the reasons for reducing fatigue strength.

Figures 26 and 27 depict a notch in the base material close to the weld toe. A semi-crack has been created in the base metal surface at the corner of a notch due to roughness of the weld. Coating material has been diffused into the crack and it can cause crack propagation into the metal. It shows that any roughness on the surface can be a location for stress concentration and crack propagation to the metal surface potentially. This type of roughness can be observed in welded galvanized surface more than non-welded specimens. In addition, we can observe more micro-cracks on the surface of the notch than other normal areas of the surface. In this regard, we noticed that welding can be a location of initiation and propagation of crack after HDG under cyclic loads.

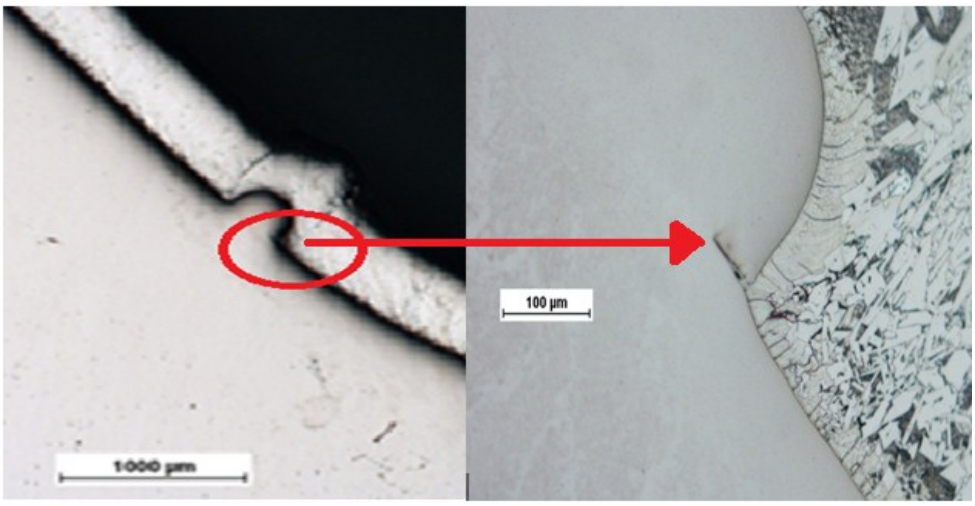

Fig. 26. Specimen No. 10, notch close to weld toe, crack initiation area.

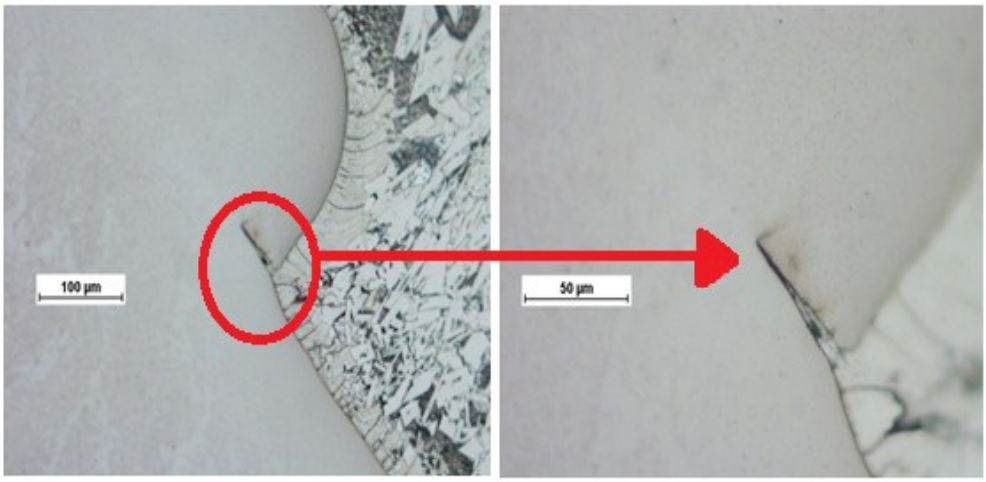

Fig. 27. Crack initiation in galvanized area and propagation to base metal.

Morphology of Coating

The bonding layer between coating and welded area was investigated by optical microscopy and SEM test. Coating in the weld area has been studied using SEM as shown in Fig. 28 for the fractured surface of the specimen No. 10. SEM observations revealed that coating is non-uniform, poorly adherent and brittle in nature.
Different coating thickness in weld area (Pa1=538.8µm), base metal (Pa2=467.4µm) and HAZ (Pa3=527.5µm) can be observed.

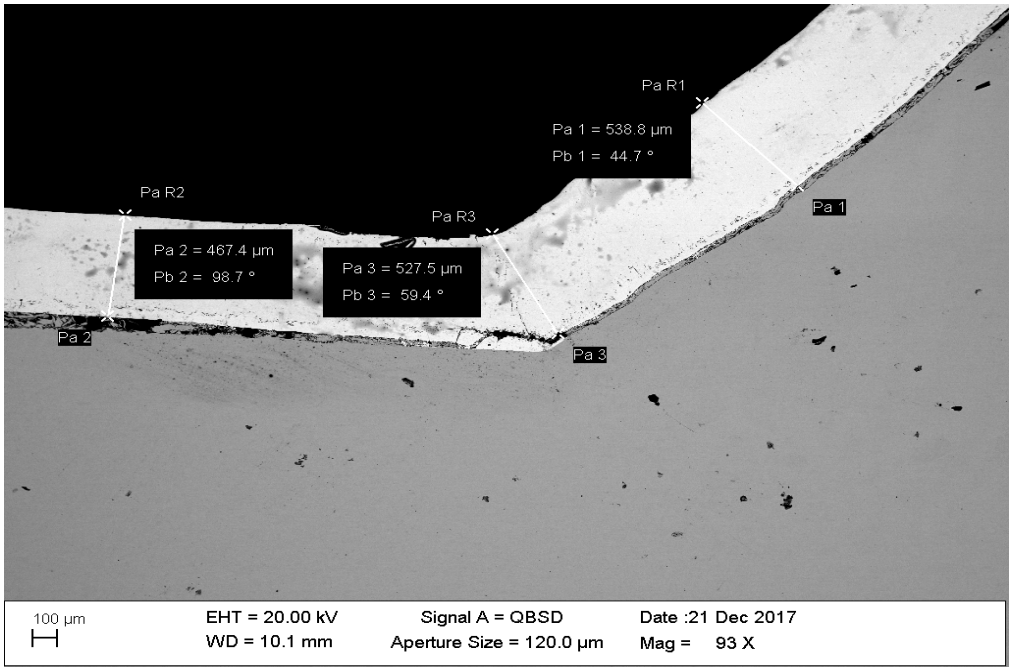

Fig. 28. SEM fracture surface of specimen No. 10 after fatigue test.

The fundamental remark, which must be pointed out, is that a crack can propagate into the steel only if it has crossed the whole thickness of the coating. This suggests that the crack in the galvanizing coating be considered as an equivalent defect in the substrate. Figures 29 shows there is not any diffusion of zinc to the steel substrate.

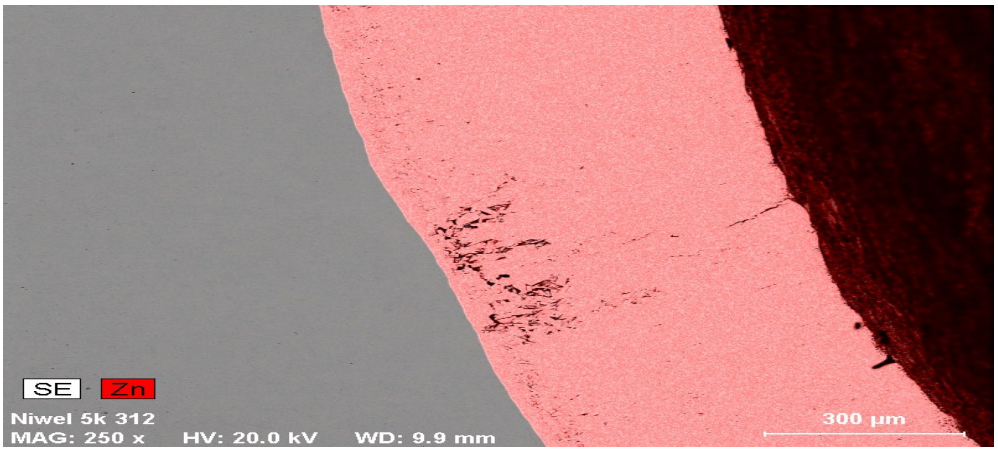

Fig. 29. Fracture surface of galvanized S_{355} after fatigue – No zinc diffusion.

In Fig. 30, SEM micrograph shows that there is not any zinc diffusion in the base material.

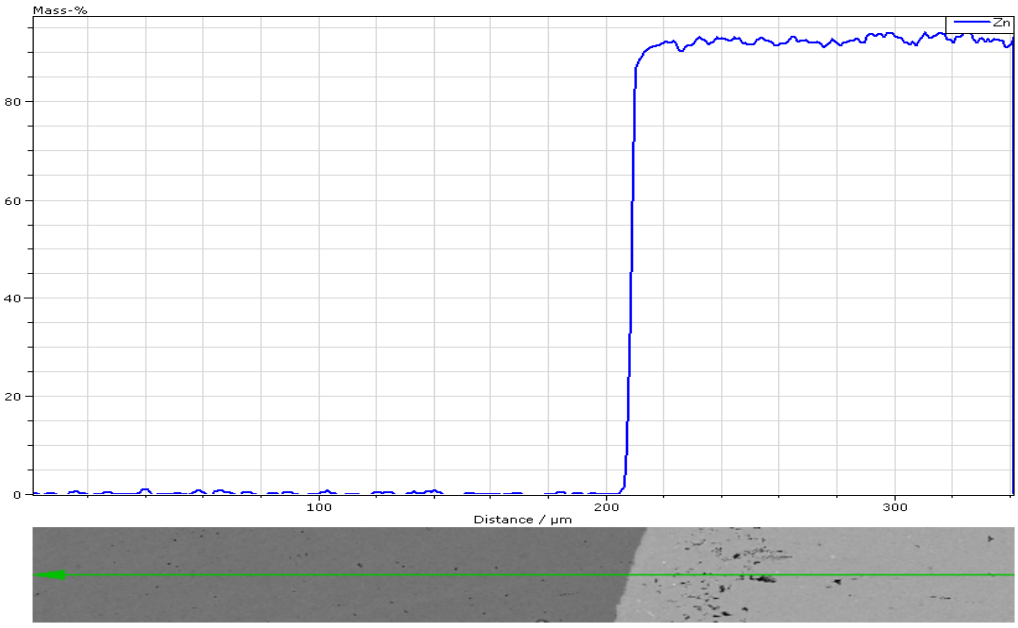

Fig. 30. No diffusion of Zinc in the steel Substrate SEM test

Specimen No. 20

Figure 31 shows specimen No. 20 which is non- galvanized and broken from the toe and root.

Initial crack appears at the weld root. Moreover, crack at the weld toe observed and propagation occurred until fatigue failure happened. Initial first crack is marked on the picture.

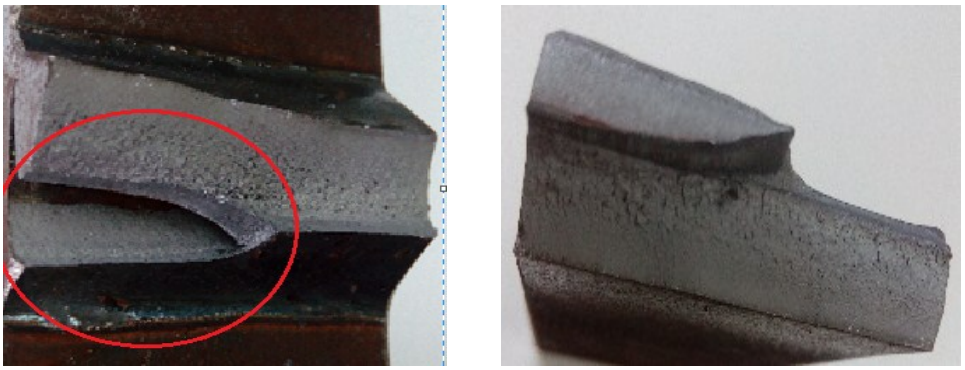

Fig. 31. Specimen No. 20 non- galvanized and broken from the toe and root.

Specimen No. 1

Figure 32 shows a galvanized sample which is broken from the weld toe during fatigue test (specimen No. 1). The specimen has been polished and etched by Nital 2%. The microstructure of the galvanized coating is shown in Fig. 33. Same as specimen No. 10, we observed notchs in the specimen No. 1, close to welding toe. Figure 33 depicts the notch and induced micro cracks in coating.

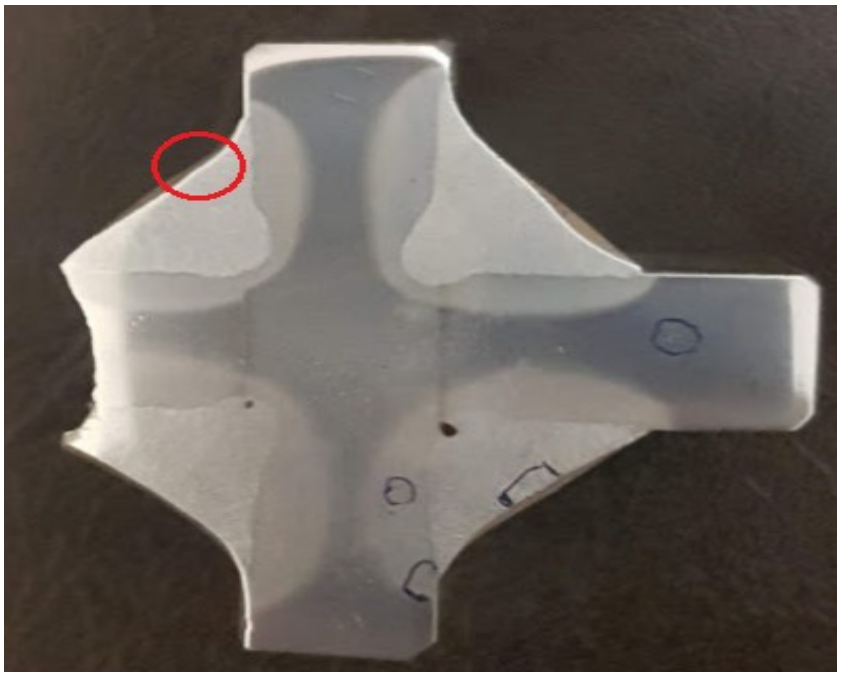

Fig. 32. Specimen No. 1. galvanized and non-broken specimen after etching.

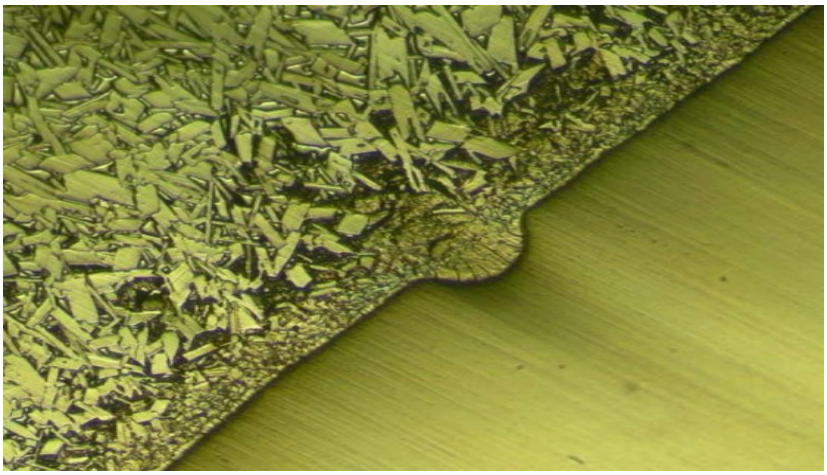

Fig. 33. Specimen No. 1, notch in galvanized coating (Mag100X).

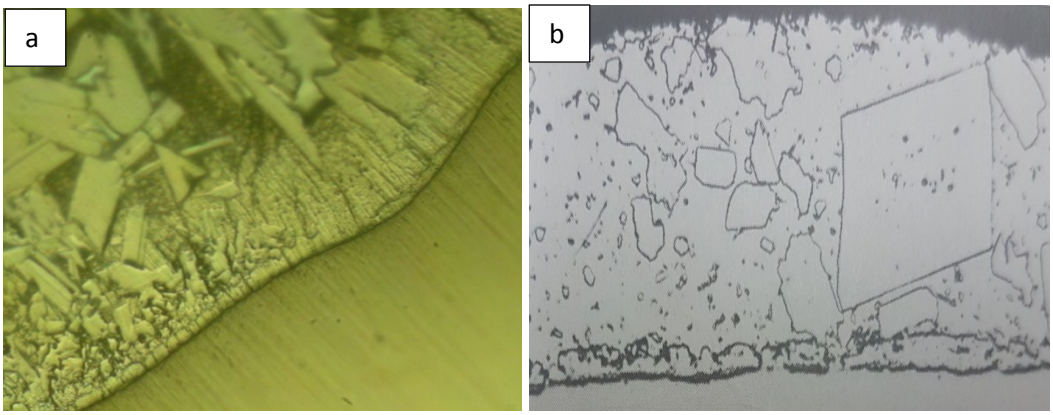

Fig. 34. Comparing galvanized microstructure of specimen No. 1 (a) with ASM handbook (b) [38].

In Fig. 34, hot-dip galvanized microstructure of the interface between base material and coating can be observed. This coating consists of Zinc-Iron compounds. We checked the ASM Handbook Volume 9 (Metallography and Microstructures).We found similar conventional cross section in section coated sheet steel [38], which shows the microstructure of hot dip galvanized steel. It can be observed that imperfection in this heavy galvanized coating consists of crystals of $FeZn_7$, which originate from dross in galvanizing bath. It means that some components in galvanization bath can make changes in the galvanized coating. Thus, it is important to know the chemical composition of the bath, also temperature and time of the galvanizing. All these parameters can affect the microstructure of the galvanization. These kinds of changing in microstructure can make the site for crack initiation.

5. Conclusions

This thesis investigates the effect of HDG on fatigue strength of fillet welded joints of S_{355} structural steel by experimental methods, such as optical microscopic and SEM tests. Attention is drawn to the need for a better understanding of fatigue performance of fillet welded and galvanized S_{355} under cyclic load. Fatigue tests were carried out on the specimens, galvanized and bare S_{355}, in low cycles to determine how much the fatigue resistance was affected by HDG. From experimental results is clear that the galvanizing process does not change fatigue strength in low cycles but based on some researches it can induce considerable reduction in the fatigue limit. Optical microscopy investigation revealed that there are many micro cracks in galvanized area, which have been induced during cooling after galvanization. By investigating galvanize coating in weld toe area some deep cracks were observed. Deep cracks stopped in the interface of coating and base material, but there is possibility to grow to the base material in high cycle loading. Some notches were revealed close to weld toe. Notches can be the site of stress concentration and crack initiation. In this investigation, some cracks were revealed in the corner of notched which have been grown to the base metal and zinc has been diffused to these cracks.

Delamination and debonding are two possible reasons for reducing fatigue strength. In our investigation delamination and debonding were observed between the coating and base material. In delamination, shear stresses arises coating from base material and makes the separation. Insufficient adhesion of the coating cannot resist to mechanical loads. At de-bonded area, holes appeared between coating and material which are sites for stress concentration leading to crack initiation and crack propagation to the base material. One of the possibilities for reduction of the fatigue strength is LME. In this study, hardness test has been conducted. As the hardness of the substrate has not been changed after galvanizing, we concluded that there is not LME. In addition, SEM observations did not show any zinc diffusion.

It should be noted that during our investigations, many defects were observed in welded area and the welded specimens did not meet the requirements of standards for filet welded joints. It is better that before fatigue test, welded specimens check and sound welds selected as specimens for testing. However, some specimens have been broken from weld toe. This shows that there is possibility that even by improving the weld quality, the fatigue life will not increase and galvanizing has more effects than weld defects on fatigue limit. A good way for checking the effect of welding quality on fatigue resistance is using finite element analysis. By comparing results of finite element analysis and experimental tests, the effect of welding defects on fatigue strength will be cleared.

Based on the results of some researches, heat treatment increases fatigue resistance but HDG reduces the fatigue strength. In continuing this research, it is good to investigate the effect of heat treatment on fatigue strength of bare material and compare the results with fatigue strength of hot-dip galvanized specimens. Moreover,

it is recommended to remove the coating from the surface and conduct the fatigue strength and get the new results. By this way, effect of micro cracks in the coating on the fatigue strength will be cleared. In order to get more accurate results, it is preferred to do more fatigue tests, especially in high cycle to check the effect of HDG on fatigue limit. For future cost-effective design and safety, further work in this area is necessary.

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