Influence of Galvanizing Process on Fatigue Resistance of Microalloyed Steels

A. Dimatteo
Department of Chemical Engineering, Industrial Chemistry and Material Science, University of Pisa, Pisa (Italy)
a.dimatteo@diccism.unipi.it

G. Lovicu, M. DeSanctis, R. Valentini
Department of Chemical Engineering, Industrial Chemistry and Material Science, University of Pisa, Pisa (Italy)

F. D'Aiuto, M. Salvati
Fiat Auto - Engineering & Design - Materials Engineering, Torino (Italy)

ABSTRACT. This paper presents the fatigue life behaviour of galvanized rear axles made of microalloyed steel. The main objective of this study is to predict the influence of the zinc protection layers on the steel fatigue life. The results show that the galvanized rear axles exhibited a lower fatigue limit as compared with the non galvanized ones. This was attributed to the cracking in the galvanized layer caused by the presence of zinc penetrating beneath the sheet surface.

SOMMARIO. In questo lavoro è stato analizzato il comportamento a fatica di un'asta posteriore inferiore realizzata in acciaio microlegato al Nb e Ti e che ha subito un processo di zincatura a caldo. Sono state, quindi, effettuate prove di fatica su banco riproducendo i carichi dovuti al peso del veicolo e le condizioni stradali. Questo tipo di prove permette intrinsecamente di considerare gli effetti del materiale, dei parametri del processo di produzione e della geometria del componente e inoltre permette di riprodurre i carichi reali al quale il componente è soggetto. Per poter ridurre le variabili in esame al solo strato di zincatura sono state poi eseguite prove di fatica a trazione compressione (R=-0.05) su provini zincati e nudi. In questo modo si è potuto evidenziare che la resistenza a fatica diminuisce nel caso di componenti zincati. Ciò è dovuto alla penetrazione dello zinco al di sotto della superficie metallica che funziona come punto di innesco delle cricche.

KEYWORDS. HSLA Steel, Galvanizing Process, Fatigue Resistance

INTRODUCTION

In recent years one of the main topics for the automotive industry has been the reduction of the weight of vehicles to increase fuel efficiency and to reduce emissions. This weight reduction has been focused mainly on the car body (ULSAB project), suspension systems (ULSAS project), and closures (ULSAC project). A very cost-effective method to reach weight savings is by gauge reduction through substitution of mild steel by high strength steel grades. Suspension systems account for a significant proportion of vehicle mass (typically 12%), alongside the main body structure (20%) and power train (18%). The prototype suspension systems developed by the Ultralight Steel Auto Suspensions Project

(ULSAS) therefore is characterized of an extensive use of high strength steels making possible substantial mass reduction. The resulting concept design revealed significant mass savings of up 34% compared with benchmarked steel suspensions, [1]. Steels in the HSLA (High Strength Low Alloy) range are hardened by a combination of precipitation hardening and grain size refining, resulting in high strength with low alloy content, [2]. This enhances weldability and choice of coatings, since these steels exhibit neither weld zone softening nor grain coarsening.
In particular, suspension components, along with wheel rims and brake components are un-sprung masses, which make weight reduction important for ride quality and response as well as for reducing the total vehicle weight. Automotive suspension has two main goals, passenger comfort and vehicle control. Comfort is provided by isolating the vehicle's passengers from road disturbances like bumps or potholes. Control is achieved by keeping the car body from rolling and pitching excessively, and maintaining good contact between the tire and the road.
The service life is the primary requirement for automotive suspension components and steels having a higher strength allow to achieve the optimum fatigue resistance, and hence higher working stress values. The service life of the parts can be increased, by others, by their surface treatment. Hot-dip galvanization of steel sheets is used to prevent their corrosion degradation. Particularly, it is used to protect suspension arms and the other automobile steel parts directly exposed to corrosion (not painted), like the under part of the vehicle, because it can produce a coating covering the whole surface with a thickness between 40 and 100 μm, [3].
The industrial galvanizing process includes a wet surface preparation procedure (including: degreasing, pickling and fluxing) followed by dipping 4 ÷ 10 min in the zinc alloy at about 450 °C. This process produces a multilayer coating metallurgically bonded to the steel substrate. Different layers are made of pure zinc (η), intermetallic Fe–Zn compounds (ζ, δ and Γ) providing sacrificial protection against corrosion, [4].
Mechanical and chemical properties of the intermetallic compounds vary from one to each other and the important variation of linear expansion coefficient of zinc and iron causes pre-existing cracks in delta phase, due to a contraction of the δ layer larger than the one of steel during cooling after galvanization, [2]. A galvanized component thus contains a pre-existing crack network which leads to the consideration of whether the reliability of the component is affected or not.
On the other hand, the influence of hot-dip galvanising on the fatigue performance has not well understood yet. It has been reported that the fatigue strength is reduced by hot-dip galvanizing. The crack nucleation mechanism proposed assumes that cracks in the hot-dip galvanised coating form rapidly during cyclic loading and then propagate into the steel substrate, [5-6]. The crack initiation phase is therefore greatly shortened.
However, on the other hand, it has been reported no influence of hot-dip galvanising on the fatigue performance of the steel substrate [7].
This study is aimed at the automotive industry, more specifically at a galvanized microalloyed steel suspension system, where safety is of great concern. Particularly, this article aims to clarify the role of the zinc coating on the fatigue resistance of lower rear axle.
A detailed analysis of the damage mechanisms are described in order to point out the key factors that influence the fatigue resistance. Component bench tests have been performed. Moreover, tensile/compressive cyclic tests have been carried on plate specimens both galvanized and not. An advantage of component testing is that the effects of material, manufacturing process parameters, and geometry are inherently accounted for. On the other hand, however, component testing does not allow to study the influence of each single variable. Thus, in order to study the only influence of galvanizing process on the fatigue resistance also plate specimens have been used. The experimental results have shown an acceleration in fatigue damage, in smooth specimens, from the rapid formation of cracks in the coating.

MATERIAL AND EXPERIMENTAL PROCEDURE

Component Fatigue Test

The fatigue analysis were conducted on the whole rear chassis as shown in Fig. 1 where the rear axles position is indicated.
The composition of the rear axle steel is given in Tab. 1.
It is a hot rolled steel microalloyed with Ti and Nb. The component was cold press formed and then hot-galvanized. Galvanizing process was carried out at 450 °C in a pure saturated zinc bath for 12 minutes. The component was first pickled in HCl at room temperature, then wet in a blanket of ammonium chloride and finally dried at 100 °C before being galvanized.

A two-post test rig (two vertical actuators that apply displacements along three principal directions to each wheel centre, reproducing the road loads), see Fig. 2, was chosen to perform the fatigue tests. In the chosen configuration the chassis is constrained to the bench by fixing it directly through the rear suspension trailing arms and dumpers.

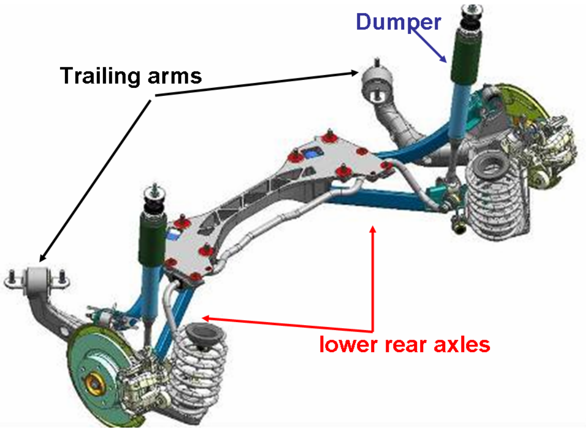

Figure 1: Automotive rear chassis system.

C	Ni	Cr	Mn	Si	Mo	V	Cu	Al	P	S	Nb	Ti
0.09	0.051	0.044	1.04	0.023	0.018	0.003	0.061	0.046	0.013	0.005	0.051	0.026

Table 1: Steel chemical composition.

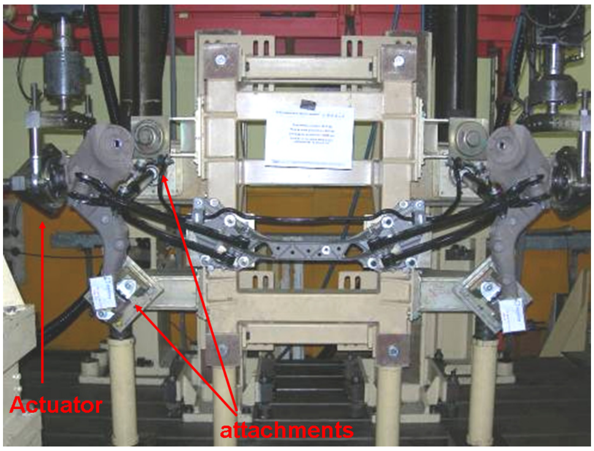

Figure 2: Component test arrangement showing details of fixturing close up.

The tests were performed under load control with constant amplitude. The frequency was 50 Hz. The load was imposed along the vertical direction of the vehicle with R=-0.5. This load ratio was chosen because it is representative of typical braking / acceleration cycles measured on vehicle.
The load, 9016 N, was chosen in order to represent the component service and, in particular, it is representative of vehicle weight and road surface (presence of potholes). Fatigue tests have been carried out on 6 specimens.

Results of Fatigue Test on Actual Component
The failure locations is positioned in bending region of the component, as indicated in Fig. 3. Fatigue cycles life was about of 120.000 cycles. The maximum number of cycles was fixed at 200.000.

The fatigue life is the sum of crack initiation and crack propagation times. However, as found in the present case, the propagation time is much shorter than crack propagation time and it can be neglected.
After test, the component was macroscopically observed in order to highlight crack initiation site. All the tested components have shown that cracks originate in the bending zone, as shown Fig. 3. A specimen was taken from this region in order to investigate the fracture surface by SEM analysis. Micrograph is reported in figure 4 where the zinc soaked into the steel working as cracking initiation is clearly visible.

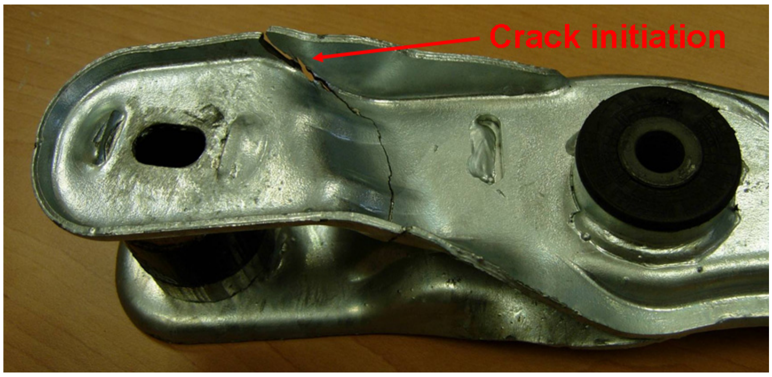

Figure 3: Failure location observed during the fatigue tests.

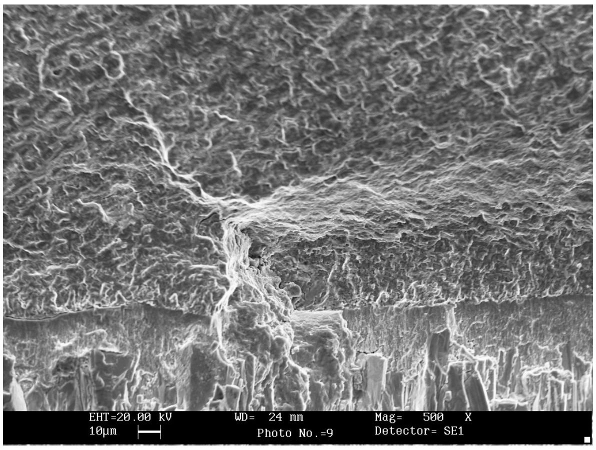

Figure 4: SEM micrograph of crack initiation.

Tensile/Compression Fatigue Test on Smooth Specimens

In order to better understand the influence of zinc layer and, in particular of the galvanized process on the fatigue resistance of the microalloyed steels, smooth specimens were tested.
Specimens were taken from microalloyed steel sheets in the rolling direction and some of them were galvanized following the same procedure as for rear axles.
Fatigue tests were executed by a closed-loop servo-hydraulic uniaxial testing machine with computer control and hydraulic-wedge grips with stress ratio (R) of -0.05. The variable loading history was chosen corresponding to typical history for the suspension system. Tests were conducted on specimens with and without protective layer.
Tensile tests were conducted, too.
Coupons from the fatigue specimens were collected and prepared for optical and SEM observation. Cracks were observed by SEM into the longitudinal section.

Smooth Specimens Results

An optical micrograph of the cross section of the zinc coating layer can be seen in Fig. 5.

Fig. 5 shows the three intermetallic sub-layers forming the hot-dip galvanized coating between η (made of pure zinc) and the steel. The coating thickness was measured and varied from 90 to 130 micron.
The microstructure of the steel is completely ferritic as shown in Fig. 6.

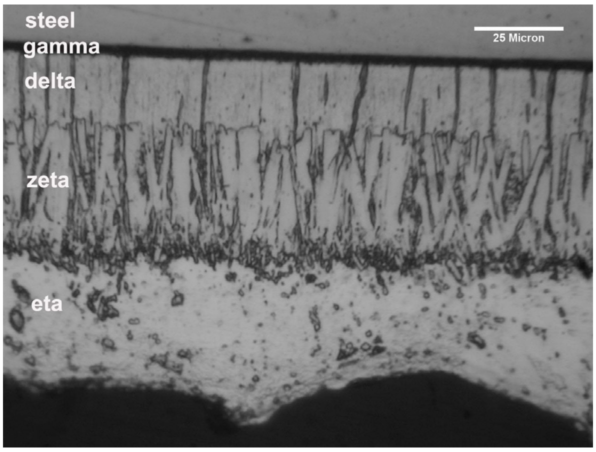

Figure 5: Optical micrograph of the hot-dip galvanized coating on the steel substrate.

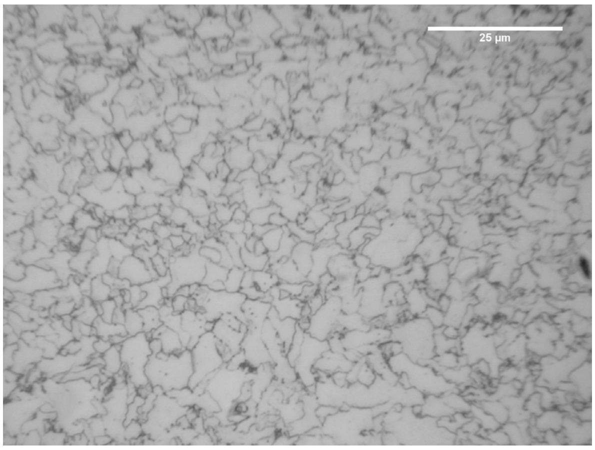

Figure 6: Microstructure of the steel.

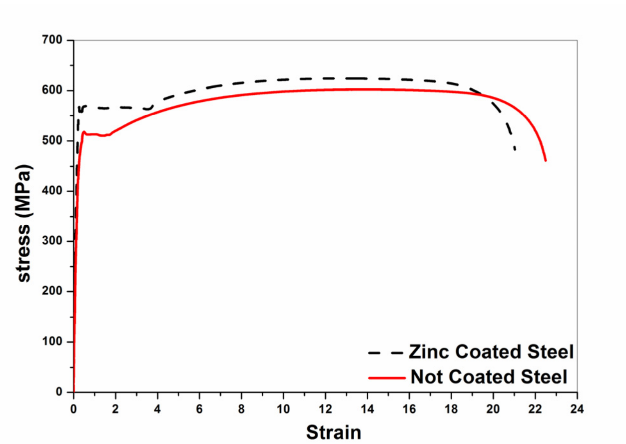

Figure 7: Stress-strain curves of coated and not steels.

Tensile tests were performed on galvanized and not-galvanized specimens. The stress-strain curves are displayed in Fig. 7. Both galvanized and not-galvanized specimens show Luders plateau at yield point. Yield and tensile strengths are, respectively, 50 and 20MPa higher for the galvanized specimens, and the Luders plateau is longer. Elongation have about the same values for galvanized and not-galvanized specimens.
Fig. 8 displays the results of fatigue tests. The fatigue limit decreases from approximately 210 to 140 MPa for not-galvanized and galvanized specimens, respectively.
SEM analysis of longitudinal section of not-coated specimens shows pre-existing cracks whose direction is parallel to the loading direction, see Fig. 9.

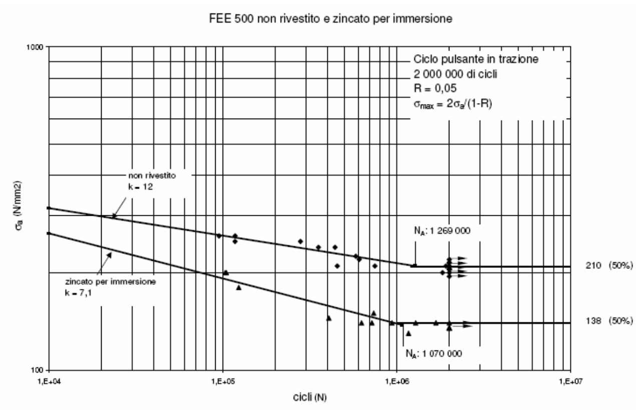

Figure 8: Stress life prediction for smooth specimen galvanized and not.

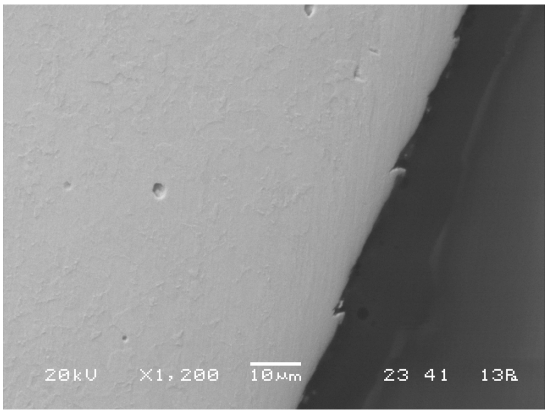

Figure 9: SEM micrography of the not galvanized steel in the longitudinal direction.

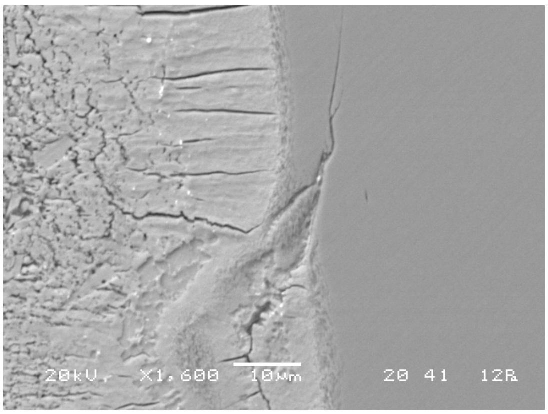

Figure 10: SEM micrography of the galvanized steel after fatigue in the longitudinal direction: cracks propagate from zinc layer to steel.

SEM analysis of coated specimens on cross section parallel to the loading direction suggest that galvanization is able to open the above-mentioned cracks already present in bare steel specimens. Fig. 10 shows the penetration of zinc layer in such cracks that induces opening. The penetration of zinc is highlighted by a SEM-EDX microanalysis mapping performed on crack area, as shown in Fig. 11.

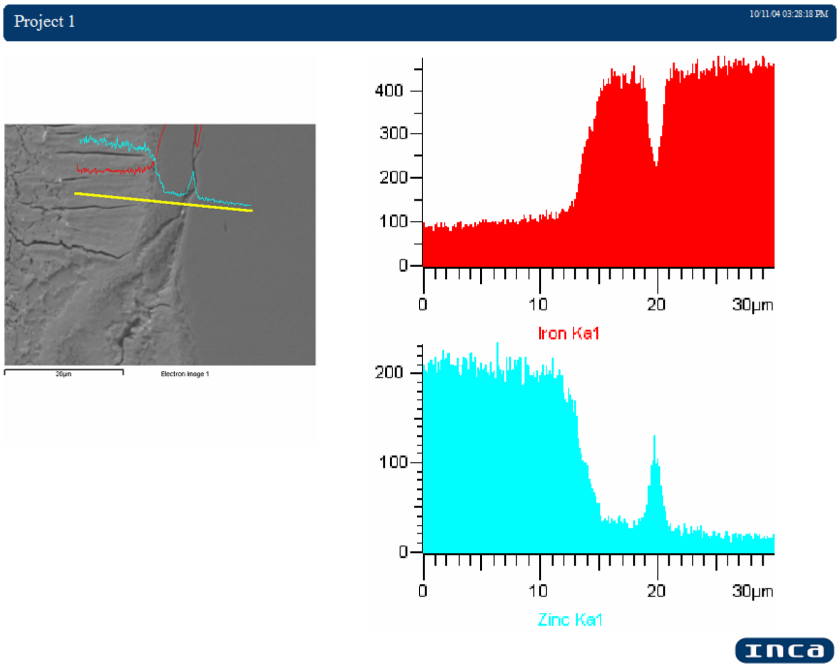

Figure 11: EDX microanalysis of the galvanized steel after fatigue in the longitudinal direction showing zinc propagation into the steel substrate.

DISCUSSION

The results of tensile tests showed that the global mechanical properties change a little after galvanization. Comparison with bare steel shows an increase of 10% for the yield strength and the extension of the Luders bands. This would be consistent with interstitial-solute segregation to grain-boundary region.

Moreover, coating process has demonstrated to influence fatigue properties of the microalloyed steel.

The SEM observations in Fig. 9 of the not galvanized smooth specimens revealed the presence of micro-cracks on the steel surface. During the galvanizing process, these damages increases steel reactivity because iron atoms in these areas are in a high-energy state and can readily dissolve in the molten zinc alloy, resulting, locally, in abnormally high iron solubility. As a results the reaction between zinc and iron can not be inhibited (by the Al-Fe layer) and local growth of the intermetallic compounds is observed directly on the steel surface. This phenomenon is called outburst and is undesirable because it has negative effect on zinc coating properties.

In Fig. 12, the typical appearance of an outburst with non uniform growth of the delta phase is shown. Furthermore, in Fig. 12, it is evident the generation of the outburst at the presence of surface defects. Thus, as shown in Figs. 11-12, the presence of outbursts is related to the presence of micro-cracks on the steel surface, and originates the penetration of the brittle zinc intermetallic compounds into the steel substrate. During the fatigue tests, these micro-cracks operate as initiation site and the presence of iron-zinc brittle compounds allows them to propagate very rapidly leading to a lower fatigue limit.

In Fig. 13, the initiation site of the fatigue crack is reported for a broken galvanized specimen. It is evident, in fact, that the crack starts in correspondence of an outburst.

Also, the fatigue cracks, in the rear axle, seems to be due to the presence of zinc penetrated into the steel, as shown in Fig. 4. Therefore, the initial surface state is responsible for the opening of cracks during the fatigue test.

In the present case, the surface finishing state before the galvanizing treatment have demonstrated to have an appreciable effect on the fatigue properties. In fact, the observed micro-cracks on the steel surface and the consequent localized growth of zinc–iron phases or outbursts and penetration of zinc-iron intermetallic compounds into steel substrate act as nucleation site for fracture. Furthermore this cracks easily propagate because of the brittleness of the zinc-iron intermetallic compounds.

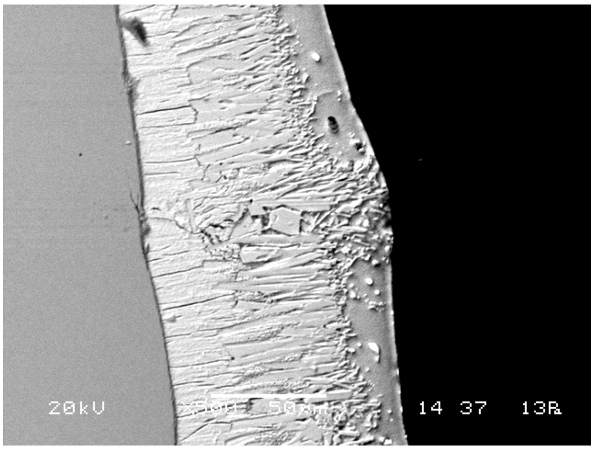

Figure 12: Example of outburst.

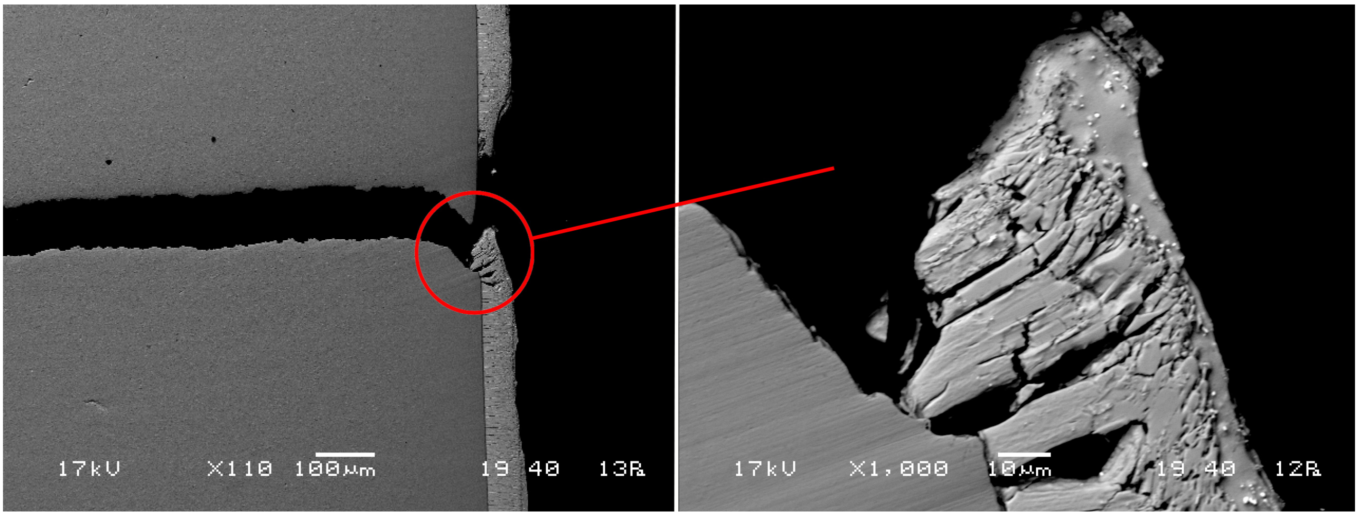

Figure 13: Example of fatigue cracks starting from an outburst.

CONCLUSIONS

In this paper, the degradation of the fatigue resistance of a microalloyed steel rear axle after galvanization has been investigated. Fatigue tests were carried out on the actual component and, also, on smooth specimens of galvanized and bare microalloyed steel to determine whether the fatigue resistance was affected by coating.

From the experimental results, it is clear that the galvanization process induces the decreasing of crack nucleation time, accelerating the fatigue cracking, both in smooth and actual component specimens.

The mechanism of the fatigue properties degradation have been highlighted on the basis of microstructural analysis. Micro-cracks originally presents on the steel surface are opened during the galvanizing process originating outbursts, and they allow the penetration of Zn-Fe intermetallic compounds into the steel substrate. Outbursts are formed by an extension of δ intermetallic layer, that is the most brittle one, at the expense of the ductile η layer. Thus, the outbursts create brittle regions on surface, allowing the cracks to initiate during the fatigue tests.

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