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Influence of Carbon Content on the Mechanical Properties of Ultra-high Strength of Coated Steel Wire

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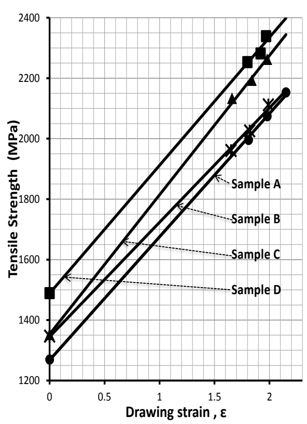
Graphical abstract



Abstract

Ultra-high strength of steel wire for offshore mooring lines can be achieved by increasing carbon content, addition of alloying elements and increasing cold work. The influence of carbon content and zinc coating on the tensile strength and torsion deformation have been investigated for drawn and hot dip galvanized steel wires at various drawing strain. In this work, experiments were conducted to increase the tensile strength of hyper-eutectoid steel wires by increasing carbon content from 0.87%wt to 0.98%wt. The samples with various diameter was drawn to their final diameter, then hot dip galvanized at 460^{o}C in a zinc bath to improve the anti-corrosion property. Torsion deformation has been investigated by twisting the drawn steel wires to different number of revolutions. Fractured samples after torsion test were analysed by optical and Field Emision Scaning Electron Microscope. The results showed that by increasing carbon content up to 0.98%wt (sample D) at drawing strain of 1.97 greatly increased the tensile strength up to 2338 MPa. However, delamination occurred at the zinc coating layer at strength exceeding 2250 MPa and the maximum limit of tensile strength of 0.92% C (sample D) is 2026 MPa without delamination. The effect of zinc coating layer on torsion degradation also revealed that the zinc alloy layer had a significant effect on delamination in the hot dip coating which associated with the higher carbon and silicon content (sample B) in the steel wires.

Keywords: Tensile strength; torsion; delamination; galvanized steel wire

Abstrak

Wayar keluli berkekuatan ultra tinggi untuk kegunaan tali tambatan di kawasan lepas pantai boleh diperolehi dengan peningkatan kandungan karbon, penambahan unsur pengaloian dan penambahan kerja sejuk. Pengaruh kandungan karbon dan lapisan zink kepada kekuatan tegangan dan ubah bentuk kilasan dikaji ke atas wayar keluli yang telah diubah bentuk dan dicelup panas galvani pada terikan tarikan yang berbeza. Dalam kajian ini, ujikaji dijalankan untuk meningkatkan kekuatan tegangan wayar keluli hiper-eutektoid bagi kandungan karbon dari 0.87%wt kepada 0,98%wt. Sampel yang mempunyai diameter pelbagai telah diubah bentuk sehingga ke diameter akhir, kemudian dicelup panas galvani pada suhu 460^{o}C dalam larutan zink untuk memperbaiki sifat kakisan. Ubah bentuk kilasan telah dikaji dengan mengilas wayar keluli tergalvani sehingga beberapa putaran. Sampel yag patah selepas ujian kilasan dianalisis dengan mikroskop optik dan mikroskop imbasan electron pancaran medan (FESEM). Keputusan menunjukkan dengan peningkatan kandungan karbon sehingga 0.98% berat (sampel D) pada terikan tarikan 1.97 akan meningkatkan kekuatan tegangan sehingga 2338 MPa. Walau bagaimanapun, delaminasi berlaku pada lapisan zink apabila kekuatan mencapai 2250 MPa dan limit maksimum kekuatan tegangan pada 2026 MPa bagi sampel B tanpa delaminasi. Kesan lapisan zink kepada penurunan kilasan juga menunjukkan lapisan aloi zink mempunyai pengaruh kepada delaminasi pada lapisan tergalvani yang mana dipengaruhi oleh kandungan karbon dan silikon yang tinggi (sampel B) pada wayar keluli.

Kata kunci: Kekuatan tegangan; kilasan; delaminasi; wayar keluli tergalvani

1.0 INTRODUCTION

The global offshore oil industry is expected to continue to grow in the coming years, driven by the depleting onshore reserves and the discovery of new large offshore reserves. With the positive outlook and the continuing trend for the offshore industry the global offshore crude oil production is expected to continue to increase. As shallow water resources decrease, deep and ultra-deep sub-salt areas will probably play an increasingly significant role in the offshore oil and gas production. Another major factor pushing for increased activity in deep and ultra-deep waters has been the advancement in new technologies. Going beyond a depth of 1500 meters, wire rope and chain start to present a number of challenges, many of which stem from the sheer weight of the mooring system [1]. In addition to needing a rather large unit to offset the weight and increasingly negative impact on variable deck load, the restoring force in the system may prove to be inadequate to provide a tight watch circle over the wellhead, which may result in operational problems [1]. In other words, as water depth increases, conventional all-steel spread mooring systems show a number of limitations both in operation and on the environment [2]. Such limitation include a lower restoring efficiency, high proportion of tether strength is consume by the vertical components of line tension, reduced pay-load of the vessel, and large mooring radius and sea-floor footprint [2]. The weight penalty of steel wire also increases rapidly with water depth and has become a significant cost driver for water depth beyond 2000 meters [3].

Nevertheless, the use of steel wires in mooring line components with increasing water depth is still possible with enhanced improvements in strength to weight ratio, which will support the extension to useful depth range and provide a more cost effective solution. To meet this trend, the strengthening of steel wire must be increased so that the rope can be made smaller, which can be achieved by increasing carbon content, addition of alloying elements and increasing cold work. A considerable amount of work has been carried out on micro-alloyed steel in the past years, particularly involving chromium, manganese and molybdenum additions [4-9]. The use of carbon content up to 0.92% C has also been shown as having potential for increasing the strength of steel rods for roping applications [10-11]. However in steel containing over 0.92% C little work has been done towards the improvement of the strength and corrosion resistance of the ropes for offshore industry. One of the fundamental problems is that there is a limit to increase the steel wire strength since strength of the patented wire is increase but the drawing amount is reduced with increasing carbon content. Another challenge is the difficulty to meet fatigue characteristics due to the embrittlement originating from cementite dissolution [12-14]. Furthermore, the mechanism of embrittlement is still not clear because there has been no consensus on the mechanism of cementite dissolution itself [15].

Strength of 4GPa and greater have been achieved by severe drawing of fully pearlitic hypereutectoid steel into fine wires [16] which is almost ten times of tensile strength of annealed mild steel. A deepwater mooring line can be a complex assembly of wire rope, chain and fibre ropes depending upon the properties required from the system [17].

In this work, the effects of chemical composition and work hardening on the tensile strength and torsion properties of hyper-eutectoid steel wires were investigated. The delamination and effect of Zn coating phases has been investigated which is related to the microstructure and mechanical properties.

■2.0 MATERIALS AND METHODS

Four different high carbon steel (0.87-0.98 %wt C) were used in the present work with the chemical composition as shown in Table 1. The steel rods with different initial diameter, d_o (11.5-13.0 mm) were first lead-patented (LP) or direct in line patented (DLP) to produce fine pearlitic microstructures. The drawing strain (ε) of steel wire was evaluated by Equation (1).

$$\text{Drawing strain}, \varepsilon = 2 \ln d_f/d_0 \quad (1)$$

Where d_f is the final diameter of wire and d_0 is the initial diameter of wire. All four steels (Sample A – 4) were then deformed by cold drawing to their final diameter, d_f (drawing strain of 1.65 to 2.15) with drawing speed of 2.5 m/sec then hot dip galvanized at 460°C in a zinc bath. The torsion ductility of the steel wires was measured by using a torsion-torque tester (ASTM A938) of rotational speed of 30 rpm. Both torque and angle of twist were recorded in real time. The tests were stopped when a sudden drop in torque was detected. For each carbon contents, 30 specimens were used to get an average of torsion value (no. of twists). Tensile tests were carried out at room temperature (29°C) using Instron Universal Testing Machine and a cross head speed of 2 mm/min with loading 0.1 to 100 kN. Delamination of the Zn-coated layer was used to assess the torsion degradation of cold drawn hyper-eutectoid steel wires. The effect of zinc (Zn) layer phases coating of the hot dip galvanizing process during cold drawing and delamination after torsion testing were also investigated. The microstructures of drawn steel were examined using Field Emission Scanning Microscopy (FESEM), Karl Zeiss Supra 55 on polished samples. The fracture surfaces of specimens subjected to torsion testing were also examined under FESEM and optical microscope.

Table 1 Chemical composition of the steel samples

Sample wire	Initial diameter, d_0 (mm)	Chemical Composition (%wt)
Sample A	13.0	0.87C-0.30Si-0.70Mn-98.1Fe
Sample B	12.0	0.92C-1.30Si-0.54Mn-0.58Cr-96.6Fe
Sample C	11.5	0.97C-0.20Si-0.70Mn-98.1Fe
Sample D	12.0	0.98C-0.60Si-0.50Mn-0.60Cr-97.3Fe

■3.0 RESULTS AND DISCUSSION

3.1 Influence of Increasing Carbon Content on the Mechanical Properties Steel Wires.

Figure 1 shows the variation of tensile strength as a function of drawing strain, ε ($2 \ln d_f/d_0$) for different carbon content of the hyper- eutectoid steel wires. Tensile strength increases with increasing of drawing strain for all samples (sample A-D) and steel contain the highest amount of carbon, 0.98%wt (sample D) exhibit higher drawing amount compare with the other steel. This attributed to the fact that sample A steel wire have finer lamellar microstructure compared to sample D steel wire as shown in Figure 2. The result shown in Figure 2 is in good agreement with other researchers that increase in strength is caused by changing in lamellar microstructure [18]. The highest tensile strength (2338 MPa) was found to be associated with the highest carbon content (0.98%wt) and finest lamellar microstructure which is for sample D.

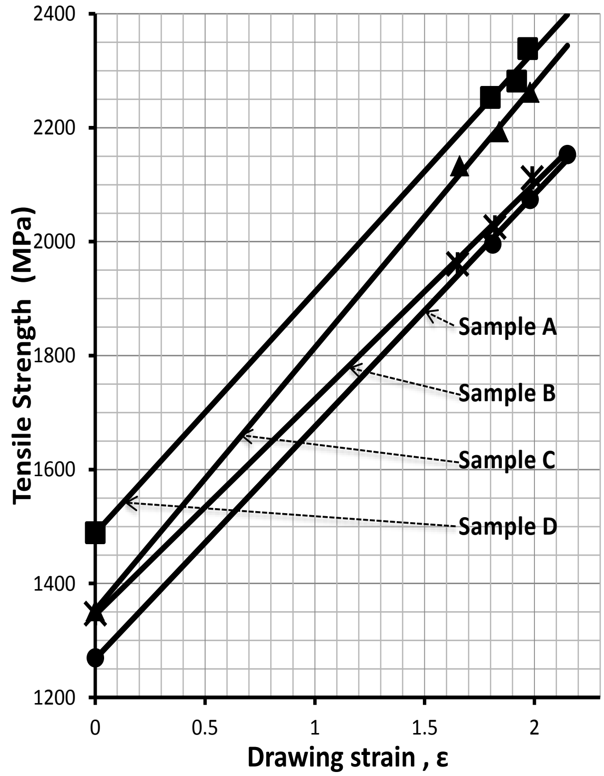


Figure 1 Tensile strength of drawn steels wires as function of drawing strain for different carbon content (sample A-D)

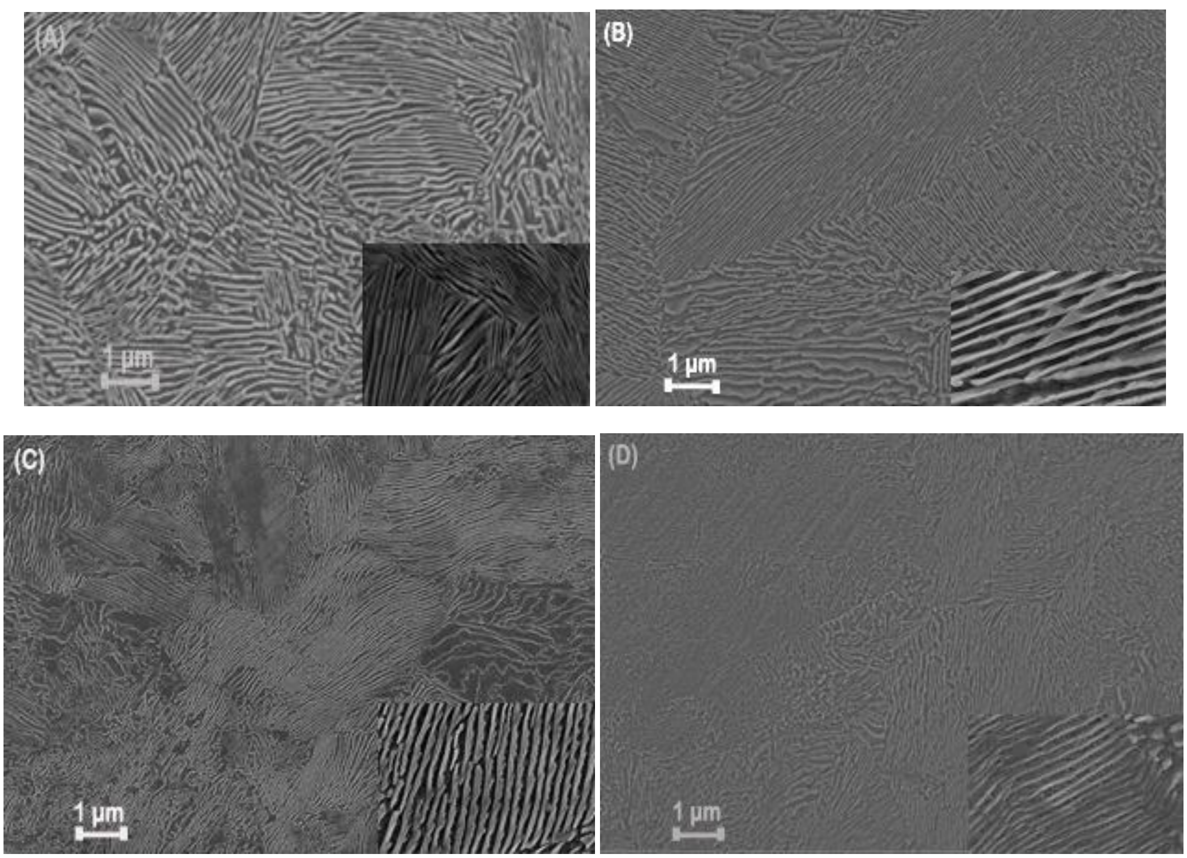


Figure 2 FESEM microstructure (polished and etched) of all samples (A) – (D)

Torsion degradation can be referred to a decrease in the torsions value before failure and also the torsion surface that is no longer has smooth and flat appearance. Torsion fracture surface are divided into three types, ranging from completely flat to very irregular [19]. Figure 3 shows the graph of torsion value versus drawing strain for all samples. It is quite clear from Figure 3, that torsion values (number of twist) for sample B, is higher than the other samples and increasing with increasing drawing amount until reaches its peak at drawing strain of 1.82 (17 turns) and then decreases due to delamination. However for sample C and sample D shows the delamination occurs at a lower torsion values and drawing strain. From the result shown in Figure 1 and Figure 3, there is clear evidence that higher tensile strength can be obtained by increasing the drawing amount and carbon content, but their torsion property will be affected. Therefore further analysis of selected sample at various drawing amount will be discussed to show the occurrence of delamination.

To investigate how the drawing limit can be increased, the mechanism of delamination was examined by using an optical and FESEM to observe the fractured surfaces and microstructural changes in the wires after torsion. Delamination is characterized by a longitudinal splitting at the wire surface during the early stages of plastic torsion deformation as shown in Figure 4. Figure 4 shows the microstructure of fractured surfaces after torsion testing for selected samples (sample B) at various drawing strain. Fracture surface of sample B at lower drawing strain ($\varepsilon = 1.65$ and $\varepsilon = 1.82$) without delamination exhibit flat fracture surface which deformed uniformly during torsion. In contrast, sample B at highest drawing strain ($\varepsilon = 1.98$) with delamination showing torsion cracks and unstable deformation pattern, and as a result, crack moved through the entire wire and result in breakage (Figure 4(c)). On measuring the torque-elapse time curve, this splitting is characterized by a sharp drop in the torque when delamination occurs as shown in Figure 5. The phenomenon of delamination has been discussed by other researcher [20] and seems to be attributable to the carbon content in the steel wires. Increasing carbon content in ferrite may result in matrix embrittlement. With carbon content of 0.87%wt (sample A), cementite decomposition will occur easily during drawing, which results in lower drawing limit. In order to achieve ultra-high tensile strength by increasing carbon content over 0.92%wt (sample B) without delamination, the analysis of zinc coating is required and will be discussed in section 3.2. Therefore, we will show the result for selected sample B to study the interface of zinc alloy coating.

3.2 Analysis on the Zinc Coating of the Steel Wire

Upon immersion of the steel wire into the molten zinc a series of iron-zinc intermetallic component (Zn alloy layer) are formed on the surface of the wire. The morphology of zinc coating on sample B at lower drawing strain of 1.65 is shown in Figure 6. From Figure 6 it is observed that the coating layer is uniform and no sign of detachment from the steel. It is clear from the results of scan analysis and EDS analysis in Figure 6 that Zn alloy layer formed at the interface of steel and zinc coating. The chemical analysis of EDS spectrum 1 (first coating layer) reveals the presence of Zn and O, spectrum 2 (second coating layer) reveals the presence of Zn and Fe and spectrum 3 (steel wire rod) are mainly Fe. This indicates that the coating layer is Fe-Zn alloy layer. At higher drawing strain, the delamination occurred and FESEM was used to observe the interaction of microstructure with cracks in sample B at drawing strain of 1.99. As shown in Figure 7, micro-cracks occur at the interface of steel-zinc coating and these micro-cracks are easily initiated during cold drawing process. Such micro-crack propagated in the direction of torsion deformation resulting in delamination (Figure 4 (c)).

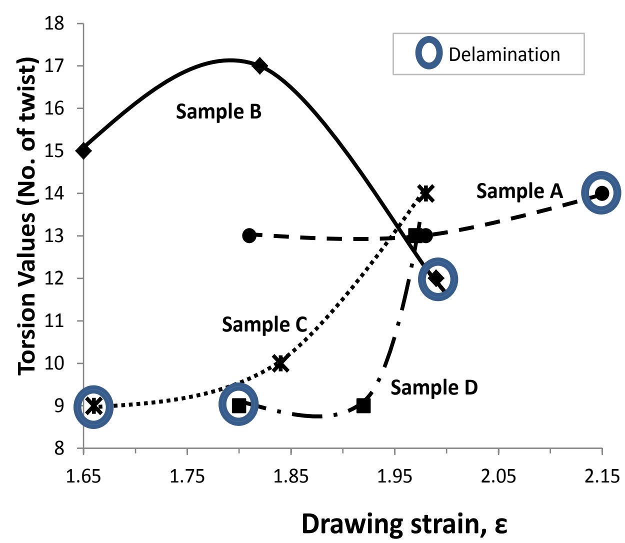


Figure 3 Torsion values versus drawing strain for sample A-D

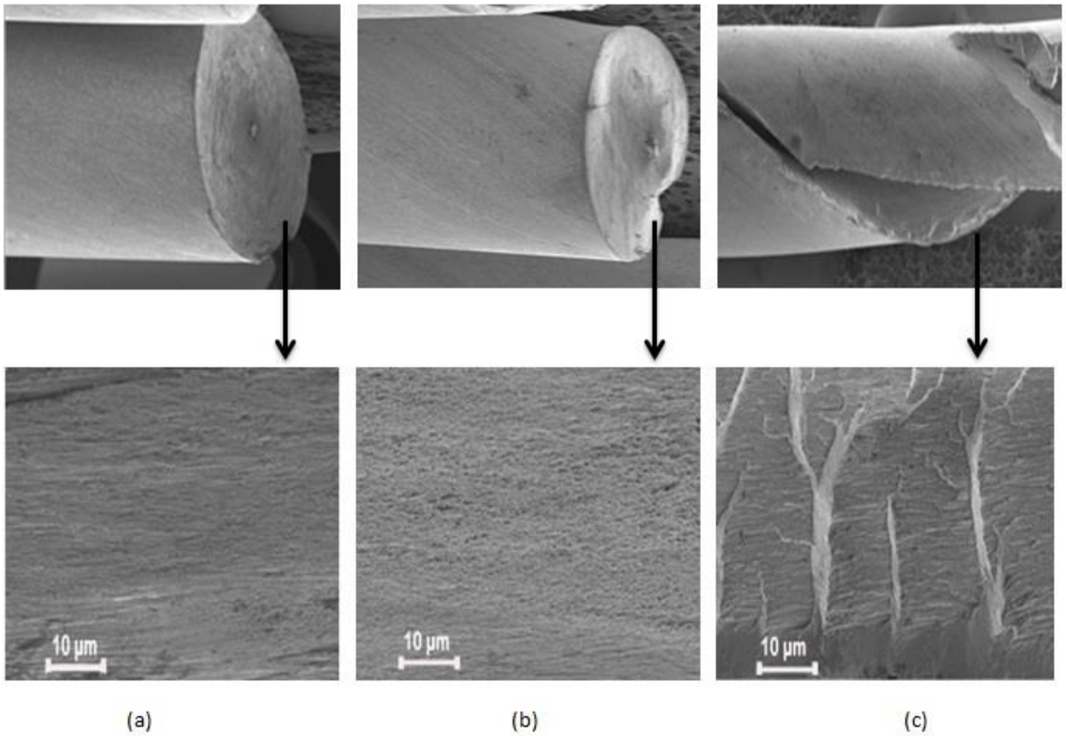


Figure 4 Fracture surface of drawn wire for sample B at various drawing strain, ε (a) ε =1.65 (b) ε =1.82 (c) ε =1.99

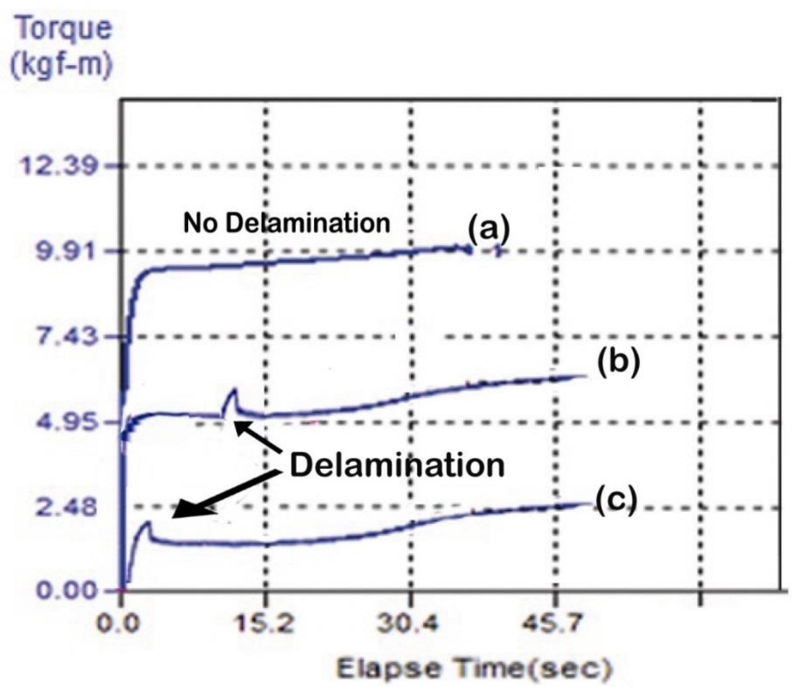
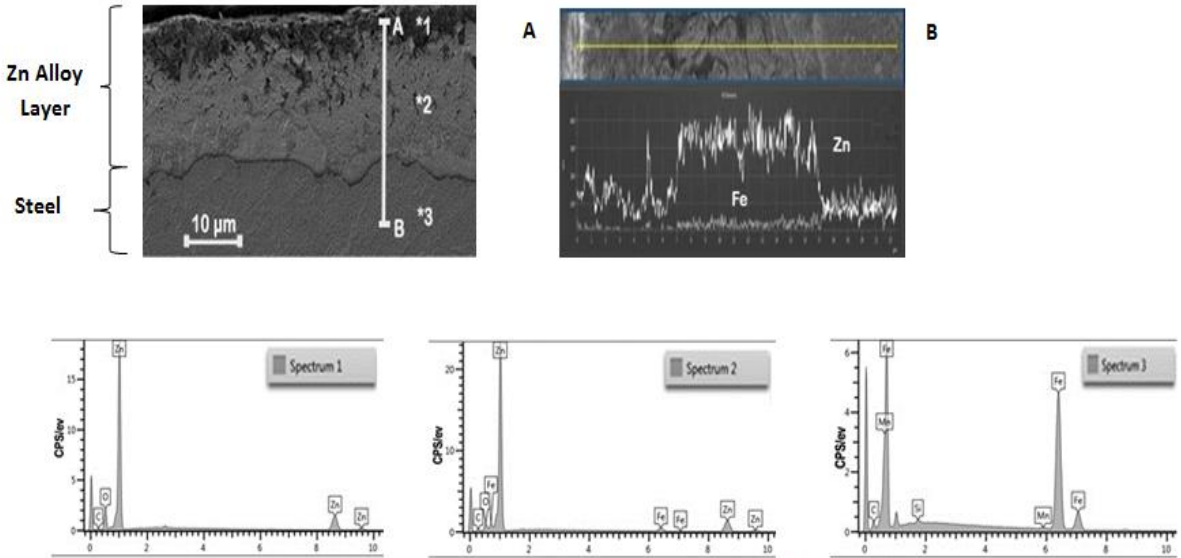


Figure 5 Torque versus elapse time for sample sample B at various drawing strain,ε (a) ε =1.65 (b) ε =1.82 (c) ε =1.99



Element	Wt%	Wt% Sigma
O	12.24	0.18
Zn	87.76	0.18
Total:	100	

Element	Wt%	Wt% Sigma
O	4.33	0.13
Fe	8.33	0.22
Zn	87.34	0.24
Total:	100	

Element	Wt%	Wt% Sigma
Si	0.29	0.05
Mn	0.78	0.12
Fe	98.93	0.13
Total:	100	

Figure 6 **(a)** FESEM micrograph , line scan and EDS spectra of zinc layer phase for sample B at drawing strain of 1.65 (no delamination)

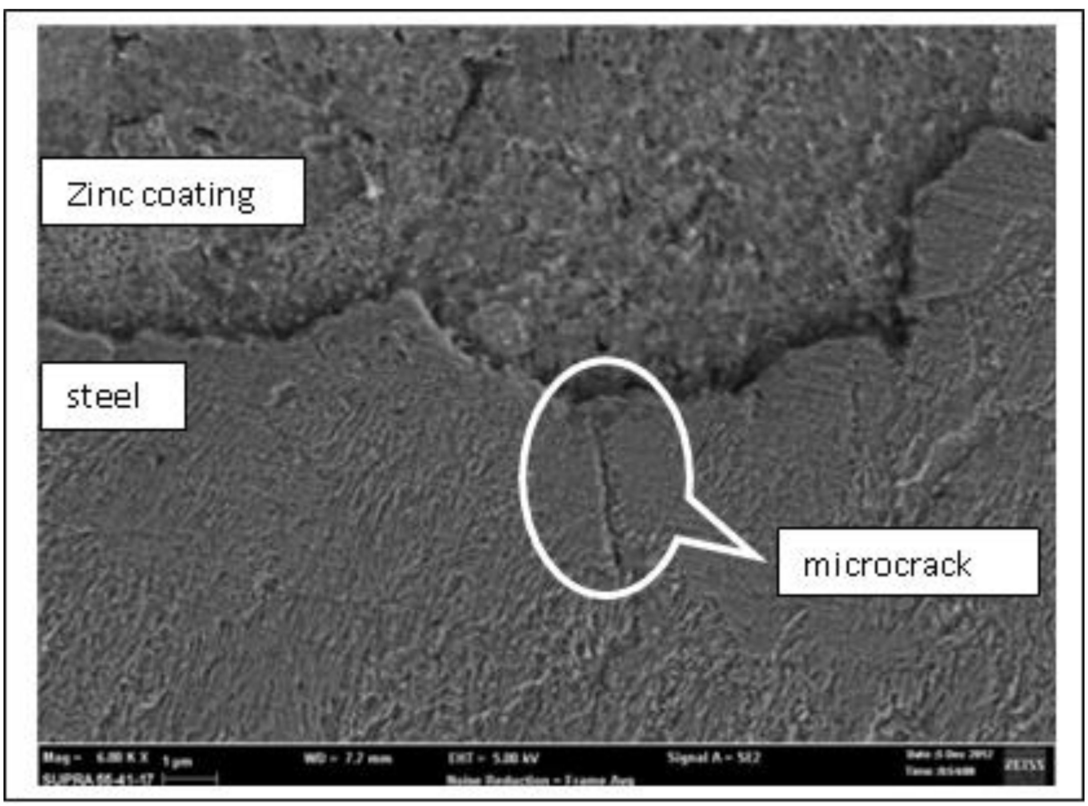


Figure 7 FESEM micrograph of sample B at drawing strain of 1.99 (with delamination)

4.0 CONCLUSIONS

In the present study, the influence of carbon content and zinc coating on the tensile strength and torsion deformation have been investigated for drawn and hot dip galvanized steel wires. The highest tensile strength (2338 MPa) at drawing strain of 1.97 can be achieved by increasing carbon content to 0.98%wt (sample D). The maximum limit of tensile strength for steel wire of 0.92%c (sample B) is 2026 MPa (drawing strain of 1.82) due to the occurance of delamination at higher drawing strain. Zn alloy layer has a significant influence on delamination as microcracks are easily initiated at the interface of zinc and steel during drawing. These microcracks propagate in the direction of torsion deformation resulting in delamination during torsion testing. Sample with high amount of carbon and silicon in the steel wires (sample B) has a negative influence on delamination as it shows the crack at the interface of steel and zinc coating at higher drawing strain.

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