International Journal of Advance Research in Science and Engineering
Volume No.07, Issue No.05, May 2018
www.ijarse.com
IJARSE
ISSN: 2319-8354

Metallurgical Characterization of Commercial High Carbon Steel Wire Rods

R Gobinath, N Naveen Kumar and G Balachandran

JSW Steel Limited, Salem Works, Tamil Nadu, (India)

ABSTRACT

A series of high carbon wire rod steel product with carbon content between 0.6 to 0.8% produced in the steel plant were analysed for their metallurgical quality. The influence of carbon content and wire rod diameter on the strength and ductility of the wire rods produced at industrial conditions were examined. The increase in carbon content increases the tensile strength while ductility decreases due to the increased pearlite content. The increase in wire rod diameter decreases strength and ductility associated with the coarse pearlite content associated with lowering of cooling rate in thicker wire rods. Based on a wide ranging plant data a regression equation was evolved to predict strength based on steel composition and wire diameter. The microstructures for varying carbon content and wire diameter were evaluated using optical microscope and SEM. The variation in interlamellar spacing as a function of carbon content and wire diameter has been established. In addition, some of the detrimental phases in some of the wire rods evaluated in the plant is brought out. This include grain boundary cementite, hard martensite associated with segregation and various deformable inclusions based on Mn-Si deoxidation.

Keywords: Grain boundary cementite,High carbon wire rods, Mechanical properties, Pearlitic microstructure

1. Introduction

High carbon wire rod products are used in applications such as wire ropes, precision springs, musical cords, bead wires, reinforcement wires for pre-stressed concrete, tire cord and suspension cables etc. The steel wire should have good mechanical properties that include high strength, good ductility, toughness, and fatigue resistance. The major factors that influence these properties are pearlite fraction, the degree of cementite network and hard phases in the microstructure. The high carbon steel wires have fine pearlite with evenly spaced cementite plates with a thickness of 0.02 to 0.04 microns and the distance between the cementite plates should be about 0.1 to 0.2 microns to maintain its high strength and to ensure its wire drawability. The final behaviour of the drawn wire depends on the raw material wire rod quality. It should have finer pearlite and should have deformable inclusions. The deformation condition and post deformation cooling affects the interlamellar spacing and ferrite fraction[1]. Various studies have reported increase in steel wire rod strength with decrease in interlamellar spacing [2-6]. The ductility of the steel is affected by interlamellar spacing and percentage of ferrite fraction. Coarse pearlite deforms inhomogeneously during cold drawing and results in strain localization in narrow slip band. Thus, thick cementite in coarse pearlite shows only limited ductility and then fractures without thinning. In fine pearlitic microstructure, thin cementite plates are fully plastic which results in achieving high strength with good ductility after cold drawing [7]. Presence of pro-eutectoid ferrite creates site for void nucleation and decreases ductility [1]. Interlamellar spacing in the order of 100 nm is required to get high values of drawing strain limit [8]. Fine interlamellar spacing avoided delamination during drawing operation. The increased interlamellar spacing caused larger sized globular cementite particles in colonies to initially align transverse to the drawing axis, that results in the occurrence of more frequent and larger sized void formation during drawing. This results in delamination during torsion [9]. Hence, a control of interlamellar spacing and ferrite fraction is desired to achieve good strength with ductility. Increasing cooling rate in a 0.67%C steel in a Stelmor cooling contributed to finer interlamellar spacing that enhanced strength[1]. Transformation temperature from austenite had strong influence on pearlite spacing, lower the transformation temperature finer the pearlite. With a lower transformation temperature, the rate of nucleation increases leading to finer pearlite lamellae [10].For steel cord application, wire rods are drawn from 5.5mm wire rods to get final wire in size range of 0.15 to 0.20 mm. During such deep drawing operation detrimental phases like grain boundary cementite, core martensite and hard inclusions can lead to wire breakage. The carbon segregation towards centre of the wire rod, results in intergranular proeutectoid cementite. This causes considerable loss in ductility and drawability of the wire rod [8,11,12]. Manganese and phosphorous segregation during casting process can result in formation of martensite island at wire rod core due to fast cooling involved in Stelmor cooling process after hot rolling. This phase is detrimental to drawabilty of the wire rod [8]. Steel cords are subjected to cyclic stress in their later process, such as push-pull torsion, bending, and stretching. They also undergo sudden stress in service like emergency brake. It has been reported that non-metallic inclusions seriously affect in-service life of tire cords, fatigue properties and may cause breakage [13]. So deformable inclusions with good plasticity, smaller volume are preferred.

High carbon steels wire rods [C=0.60 to 0.80%] with diameters between 5.5 to 13 mm are manufactured by JSW steel Ltd for a wide variety of customers. The present study investigates the metallurgical characterization of a range of as-hot rolled high carbon wire rod steel products with respect to the steel chemistry, microstructure and its correlation to the tensile strength [UTS] and ductility as measured by reduction in area [% RA].

2.0 Experimental work

The primary molten steel in JSW Steel Salem Works was made using mini-blast furnace hot metal in an oxygen blown Energy optimisation furnace [EOF]. The molten primary steel from EOF was alloyed in a ladle furnace, with required ferroalloys to achieve the desired steel chemistry. The molten steel was subjected to Si-Mn deoxidation and vacuum degassing treatments. The final molten steel made as per chemistry was continuously cast in to 160x160 billet. The billets were hot rolled in the bar rolling mill at rolling temperatures between 1050 to 1150°C, where a trio rolling mill followed by a horizontal vertical mill. The bars are further rolled to required size by a Kocks finishing mill. The wire rods after Kocks mill is passed through a Non-Twist Mill through an intermediate water cooling box. The product is formed into coil through a laying head. The layed coil is cooled using a Stelmor cooling bed with a pre-determined cooling air draft. It is usual to record the tensile strength and ductility as measured by reduction in area for each grade and that was produced in the plant. In the present study, the ladle furnace chemistry and the as-rolled mechanical properties of the production data generated from wire rods 5.5 to 13mm diameter bar were considered for analysis. An average value of more than 10 data minimum was considered in each grade and each cross section of the product. The ladle furnace chemistry of the steel was analysed using ARL make optical emission spectrometer. The tensile test was tested using FIE make tensile machine. The microstructure of the sample was characterised using a Carl Zeiss make optical microscope with image analysis capability. Select samples in each grade were characterised using Carl Zeiss Scanning electron microscope. Segregation analysis of the wire rod sample was analysed using SEM-EDS.

3.0 Results and Discussions

High carbon wire rod steel is an important product of JSW Steels Ltd., sought by prime customers for subsequent wire drawing application for several end uses such as bead wires, spring wires etc. Most steel wire rods supplied are evaluated for their chemistry, microstructure, tensile strength and %RA. The relative performance of the output quality of the various grades and sizes enables the assessment of the physical metallurgical behaviour of the high carbon wire rod steels. In the present study, the properties are measured as a function of chemical composition [0.6 to 0.82% C] and wire rod diameters [from 5.5 to 13 mm]. The high carbon wire rod steel grades studied is shown in Table 1. In each grade and diameter, at least a minimum of 10 different mechanical property data was averaged out.

TABLE 1 Chemical composition of the various grades studied

Grade	C	Si	Mn	P	S	Al	Cr	N	Ti
58/62	0.60	0.24	0.59	0.012	0.006	0.003	0.053	0.0065	0.0016
61/65	0.63	0.25	0.62	0.012	0.005	0.003	0.048	0.0067	0.0011
66/70	0.68	0.22	0.63	0.014	0.005	0.003	0.051	0.0068	0.0018
71/75	0.72	0.24	0.63	0.013	0.003	0.003	0.050	0.0053	0.0019
76/80	0.78	0.22	0.70	0.017	0.006	0.003	0.071	0.0067	0.0010
81/85	0.82	0.23	0.68	0.013	0.003	0.003	0.067	0.0055	0.0012
BRM001	0.78	0.22	0.72	0.014	0.004	0.003	0.100	0.0062	0.0018
HC70	0.68	0.22	0.62	0.014	0.002	0.005	0.050	0.0053	0.0019
HC75	0.74	0.24	0.64	0.013	0.002	0.003	0.053	0.0050	0.0018
HC80	0.78	0.20	0.69	0.019	0.003	0.003	0.050	0.0060	0.0015

IJARSE
ISSN: 2319-8354

3.1 Process Analysis

The coils are produced as an output of a non-twist mill as per schedule shown in Fig.1 ((a) and (b)). A 160x160 mm^2 billet was reheated in a furnace to the rolling temperature of about 1170°C followed by high pressure descaling. The high carbon wire rods have good workability range between 950 to 1200°C. The cast billet is subject to roughing in a 3-High reversible rolling mill, where a 2:1 reduction ratio with 5 pass breaks down the initial as-cast structure at high temperatures. This followed by three trains of horizontal-vertical [HV] mills.The first train with 6 stand gives a reduction ratio of 3.85 and the second train with 6 stand gives a reduction ratio of 3.7 and third with 2 stand, a reduction ratio of 1.5 is achieved. The reduction ratio is higher in the first two trains to ensure higher degree of hot working as the temperature is higher, where higher effective strain is achieved promoting dynamic recrystallization towards the

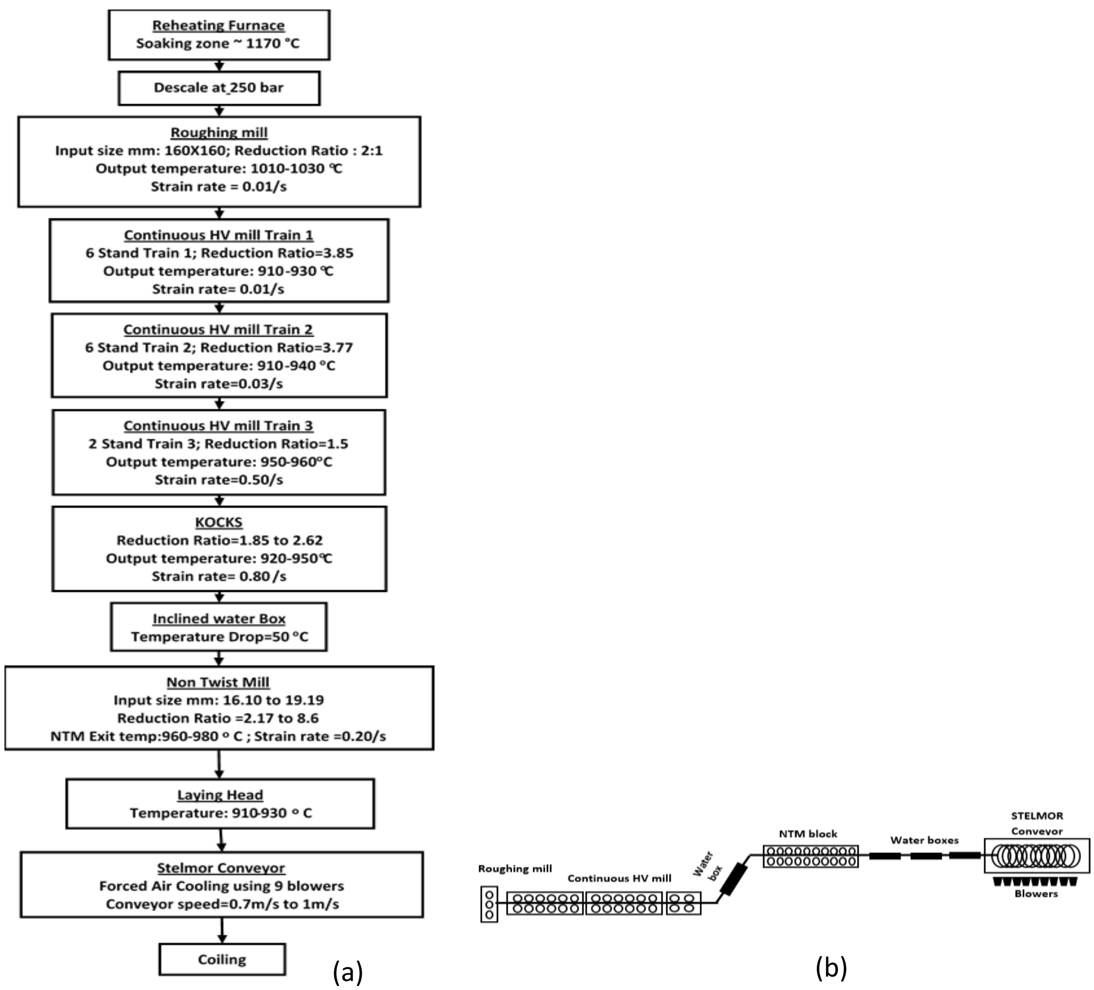


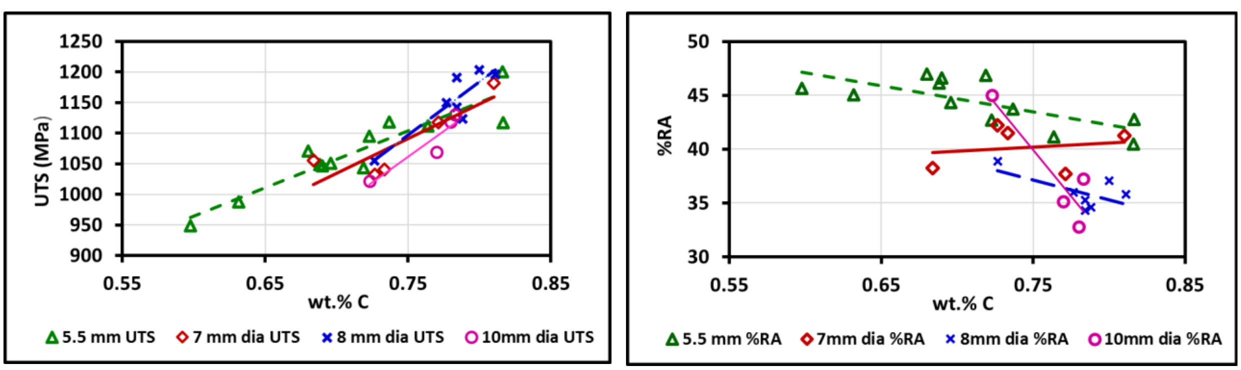
Fig. 1(a) Process flow chart for the bar rolling mill for a typical 5.5 mm wire diameter (b) The process route for the production of wire rod coils through NTM route.

IJARSE
ISSN: 2319-8354

steel core. The last train has lower temperature and lower reduction ratio. This is followed by the cross section being shaped to rounds in a Kocks mill where a reduction ratio of 2.62 is maintained. The temperature range in the HV mill and Kocks mill remains between 910 to 960^{o}C.The wire rod is subject to further cooling in a water box to compensate for higher adiabatic rise in temperatures that develops in the Non-twist mill reduction. The reduction ratio varies from 2.17 to 8.6 at this stage and wire rods with diameters varying between 5.5 and 13 mm is manufactured. The temperature after NTM increases above 980^{o}C which is controlled at laying head to less than 930^{o}C. The coiling of the wire rod is carried out through a laying head on a Stelmor conveyor with a draft from 9 blowers. The conveyor speed is varied from 0.7m/s to 1m/s depending on the grade. Cooling conditions in the Stelmor conveyor decides the microstructure in the steels. During cooling, recalescence take place at a temperature of about 640 to 650^{o}C, where the austenite phase transforms to the pearlite and ferrite phases [14]. The phase transformation is a function of the cooling rate encountered by the wire rod thickness. This in turn depends on the carbon contents, alloying elements and the wire rod diameters. The typical cooling rates encountered is of the order of 10 to 15 ^{o}C/s in the range of wire rods manufactured as measured by the hardness range achieved in the present study.

3.2 Effect of Carbon content on Mechanical Properties and Microstructure

The effect of carbon content on the tensile strength [UTS] is shown in Fig.2(a) and ductility [%RA] in Fig.2(b) of the various wire rods produced.



(a) (b)

Fig. 2(a) Tensile strength of the steel made as a function of carbon content and bar diameter (b) Ductility of the steels made as a function of carbon content and bar diameter.

The graphs also bring in the variation as a function of the wire rod diameter. It is generally observed that with increasing carbon content, the tensile strength is increasing and correspondingly there is a decrease in ductility. Smaller diameter products show marginally higher strength and higher ductility than the larger diameter wire rods. The increase in the strength with loss in ductility of the wire rod with carbon content may be attributed to the increase in the pearlite content in the steel. As pearlite plates nucleate crack easily, ductility is reduced. For all the wire diameter, the tensile strengths follow almost similar slopes with increasing carbon content. The 10 mm diameter wire rod shows sharper ductility fall. This may be associated with slower cooling rates in higher diameter wire rod which promote coarse lamellar pearlite and grain boundary cementite.

The microstructure of a typical 5.5 mm wire rod with increasing carbon content is shown in Fig.3. There is a decrease is ferrite fraction with increasing carbon content in Fig.3. Similar trend is seen in other wire diameters as well. A decrease in ferrite start temperature with carbon content has been reported [3,15]. Steels with hypo-eutectoid composition show lower fraction of pro-eutectoid ferrite, while the hyper-eutectoid steels show fully pearlitic matrix. This is evidenced in the microstructures. With increase in the carbon content of the steels the interlamellar spacing also becomes finer in the SEM micrograph in 5.5mm wire rods as in Fig.4. As the carbon content increases, the driving force of austenite to pearlite increases [5] and the diffusion path of carbon is reported to be shorter [16]. Hence, the carbon atoms do not have to travel so far as the carbon supply is easily maintained. This makes interlamellar spacing finer with increased carbon content. Similar decrease in interlamellar spacing with increase in carbon has been reported by other studies [5,16].

High carbon wire rods derive their strength from solid solution alloying [C, Si and N], ferrite fraction, grain size and interlamellar spacing as governed by Gladman equation[2]

$$\sigma_{UTS} = f_\alpha^{1/3}\left[247 + 1146\sqrt{\%N} + 18.2d^{-\frac{1}{2}}\right] + \left(1 - f_\alpha^{\frac{1}{3}}\right)\left[721 + 3.55S_0^{-\frac{1}{2}}\right] + 97.3\%Si) \quad (1)$$

where,

σ_{UTS} = Ultimate tensile strength (MPa); fα = ferrite volume fraction; d=ferrite grain diameter (mm); S_o=interlamellar spacing (mm), N= wt. % N; Si = wt.%Si.

Campbell modified the equation further as below [3],

$$\sigma_{UTS} = f_\alpha^{1/3}\left[197 + 19.7d^{-\frac{1}{2}}\right] + \left(1 - f_\alpha^{\frac{1}{3}}\right)\left[421 + 9.19S_0^{-\frac{1}{2}}\right] + 150\ .\%Si \quad (2)$$

The measured tensile strength in the present study was found to be higher than both that predicted by Gladmann [equation (1)] and Campbell [equation (2)]. Other studies have reported similar inconsistencies [1]. As there was a wide range of tensile data generated in the steel mill, a regression equation was evolved to predict the UTS (MPa) based on alloying elemental concentration [in wt.%] and the wire bar diameter [dia in mm]. The equation is shown below

UTS (MPa) =-940*C-4285* %Si-1445* %Mn-6610* %P +3670*%C*%Si+2289*%C*%Mn +4008*%Si^2-49.98*dia*%C+982*dia* %P +23.41* (dia) -0.599*dia^2 +1895 (3)

The above equation is valid for size range of 5.5mm to 13mm wire rod with composition range % C=0.58 to 0.80; % Si=0.16 to 0.30; %Mn= 0.45 to 0.80; %P= 0.007 to 0.026; %Cr < 0.050. The validity of the regression equation was verified with plant data and also some of the steel composition in published literature as in Table 2. It is seen that the data is very close to measured values. The grain size in the steel is influenced by the laying head temperature, the degree of deformation in the final pass, water cooling and the air draft in Stelmor cooling bed and speed of coil movement. The microstructures studied in the range of steel studied show a ferrite grain size in the range of 20-30µm and interlamellar spacing is in the order of 100 to 300nm.

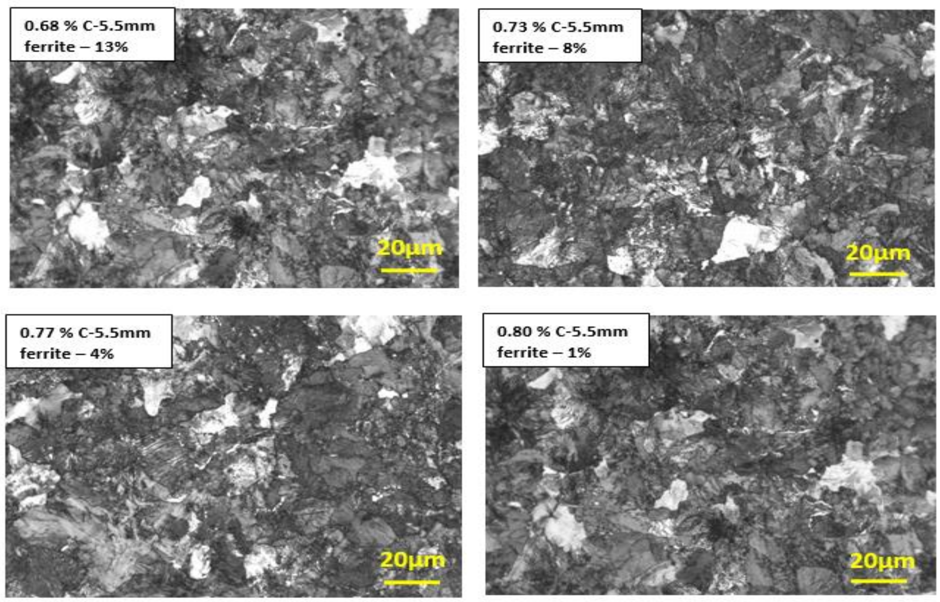
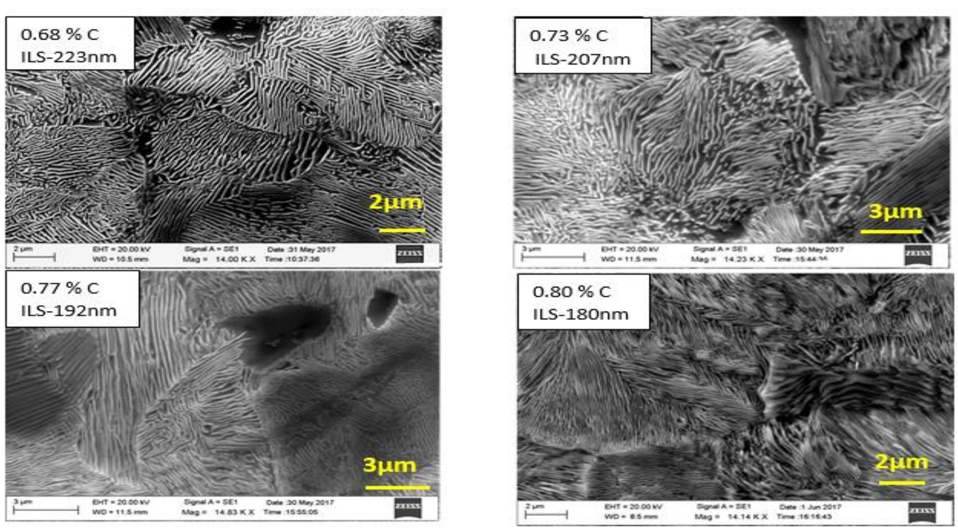


Fig. 3 Microstructural variation with varying carbon content in a 5.5 mm wire rod.



IJARSE
ISSN: 2319-8354

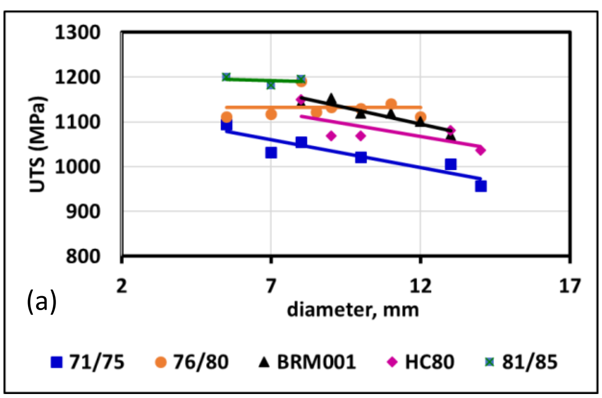
Fig. 4 SEM micrograph showing the variation of interlamellar spacing [ILS] in 5.5mm wire rod at R/2 location with variation in carbon content.

Table 2 Validity of the regression equation on the literature data with predicted strength values

Composition in wt.%	Wire rod diameter mm	Literature reported value UTS (MPa)	Predicted value UTS (MPa)	Reference
0.80 C-0.20Si-0.70Mn-0.02P	6	1170	1168	[8]
0.85 C-0.20Si-0.70Mn-0.020P	6	1220	1223	[8]
0.73 C-0.23Si-0.53Mn-0.014P-0.03Cr	6.5	1070	1057	[17]
0.71 C-0.21Si-0.51Mn-0.011P-0.02Cr	6.5	1020	1037	[17]
0.62 C-0.20Si-0.50Mn-0.008P	5.5	940	988	[18]
0.72 C-0.20Si-0.50Mn-0.008P	5.5	1030	1054	[18]
0.83 C-0.20Si-0.50Mn-0.008P	5.5	1130	1127	[18]

3.3 Effect of bar diameters on Mechanical Properties and Microstructure

The effect of bar diameter on the tensile strength and ductility is brought out for select grades in Fig.5(a)-(b). It is observed that as the diameter increases, the strength level and ductility both decreases marginally. This is mainly due to the variation in ferrite fraction and interlamellar spacing with wire diameter. As wire diameter increases, the cooling rate towards the wire rod core decreases leading to coarse microstructure. The variation in ferrite fraction with increase in wire rod diameter for a typical 0.80 % C steel as observed in optical metallography is shown in Fig.6. The interlamellar spacing measured in the 0.8% C steels at various diameter observed in SEM is shown in Fig.7. The interlamellar spacing (λ) is inversely proportional to the degree of undercooling ($\lambda \propto 1/\Delta T$). The Fig.5(a) shows that out of the five grades plotted, the grades 81/85 and 76/80 the strength decrement is not significant compared to other grades where there is fall in strength. The ductility fall with diameter is however uniform for all grades. This is probably due to coarser microstructures.



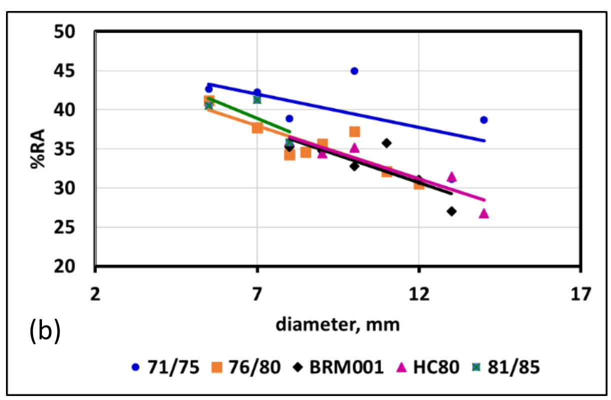


Fig.5(a) Tensile properties of the steel with increasing wire rod diameters (b) Ductility of the wire rod as a function of wire diameter

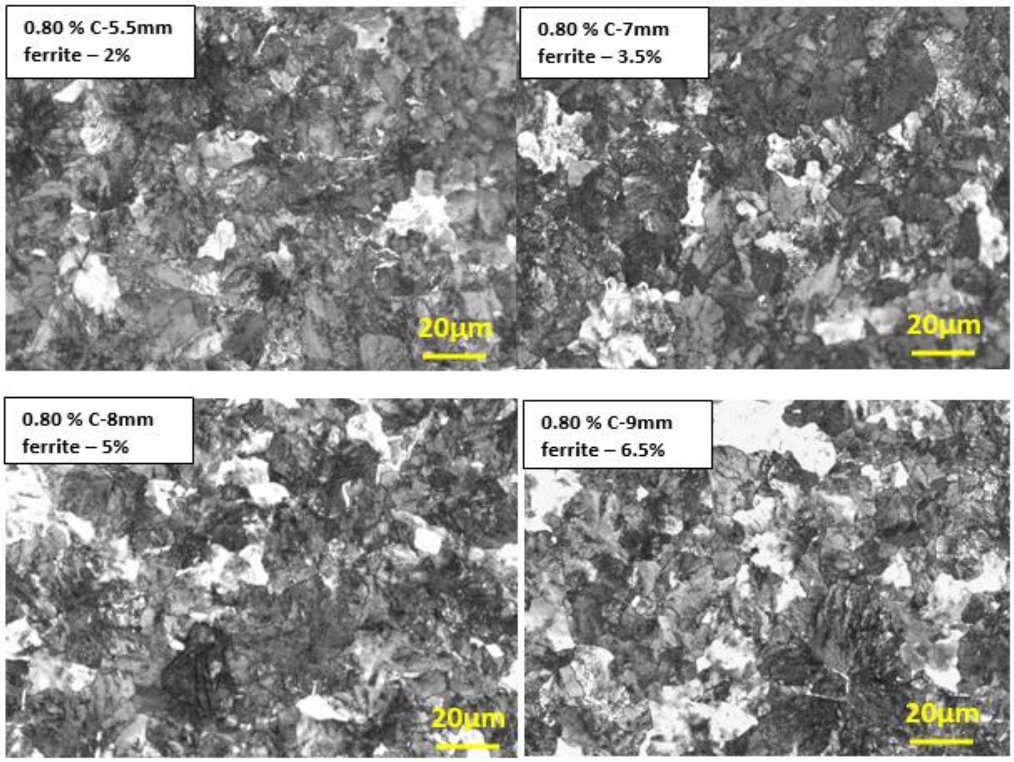


Fig.6 Microstructural variation in a 0.8%C steel wire rod with varying wire rod diameter.

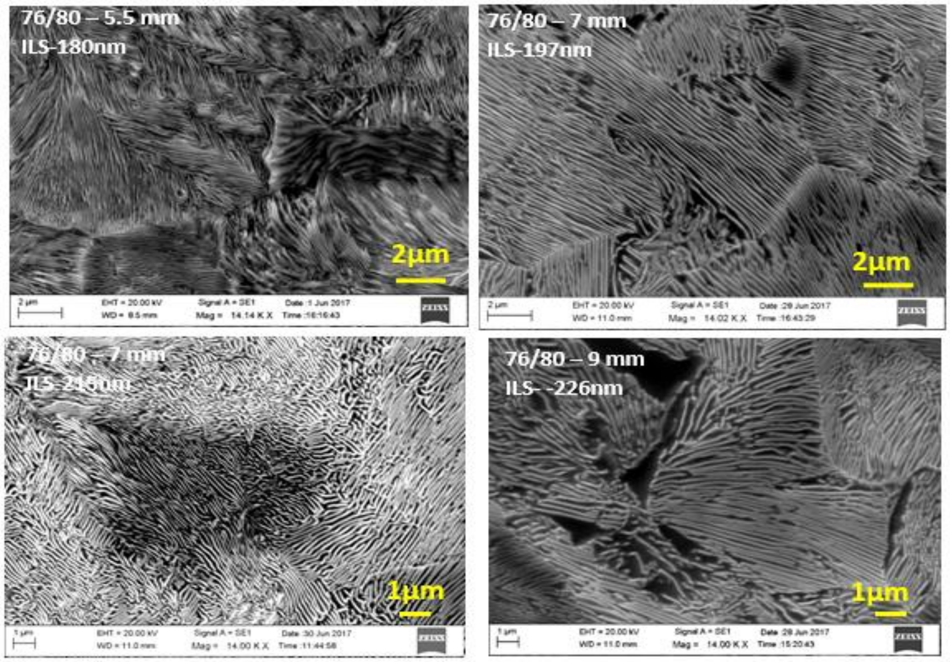
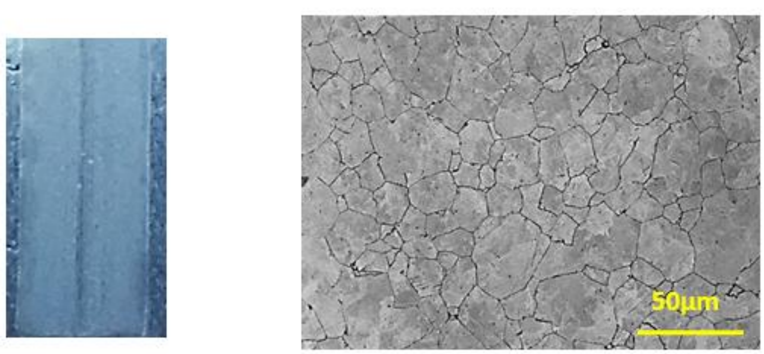


Fig.7 SEM microstructure of a 0.80%C steel with varying diameter at R/2

3.4 Detrimental phases in high carbon wire rods

There are some undesirable phases observed in some of the wire rods that has potential to affect the subsequent processing such as wire drawing. The hypereutectoid steels have equilibrium tendency towards forming grain boundary cementite. Hence, steels with higher carbon content and with low cooling rate are prone for grain boundary cementite formation. Hence, in hyper eutectoid steels faster cooling after coiling in laying head is critical to suppress the grain boundary cementite formation. Even in the hypoeutectoid high carbon steels, the inherent nature of solidification in processes such as continuous casting lead to some level of segregation that promote grain boundary cementite especially towards the core zone. The centre line segregation in a cast bloom tend to remain in a wire rod in spite of the very high reduction ratio. A typical 0.8%C steel with 10mm diameter was found to show the macro segregation effect in optical as in Fig.8(a) and the optical micrograph shows the grain boundary cementite as in Fig.8(b).

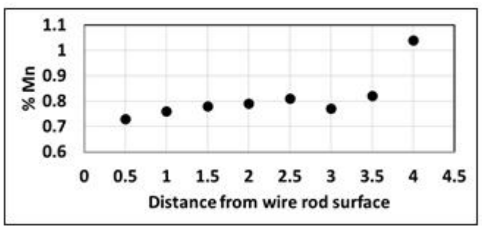


(a) (b)

Fig. 8 Grain boundary cementite occurrence in10 mm 0.8% C wire rod (a) Macrostructure of wire rod showing centre segregation; (b) Optical microstructure of the grain boundary carbide

Another detrimental phase that forms in high carbon wire rods is the formation of hard martensite phase as in Fig.9. The presence of this phase hinders the wire drawing operation even if it is of minor size. The formation of martensite is attributed to the shift in the CCT diagram to the right associated with carbon and micro-segregating elements such as Mn, Cr and P and cooling rate experienced by the wire rod. The typical martensite at the wire rod core in a typical 0.8%C containing 8mm diameter wire rod is shown in Fig.9(a). At the martensite region, the hardness value of 810HV was found. It has been reported in literature that Mn and P can enhance martensite formation [8]. The Mn level was examined in several wire rods using SEM EDS analysis across the radius. In one of the 8 mm wire rod of 0.8%C-0.76% Mn steel, the Mn content distribution followed analysis as in Fig.9(b). An increase in Mn is seen towards the core and this has potential to form martensite.

a)



b)

Fig.9 (a) SEM microstructure showing core martensite in 8mm 0.82% C steel wire rod with 810 HV hardness (b) Manganese variation in the wire rod as measured by SEM – EDS

IJARSE
ISSN: 2319-8354

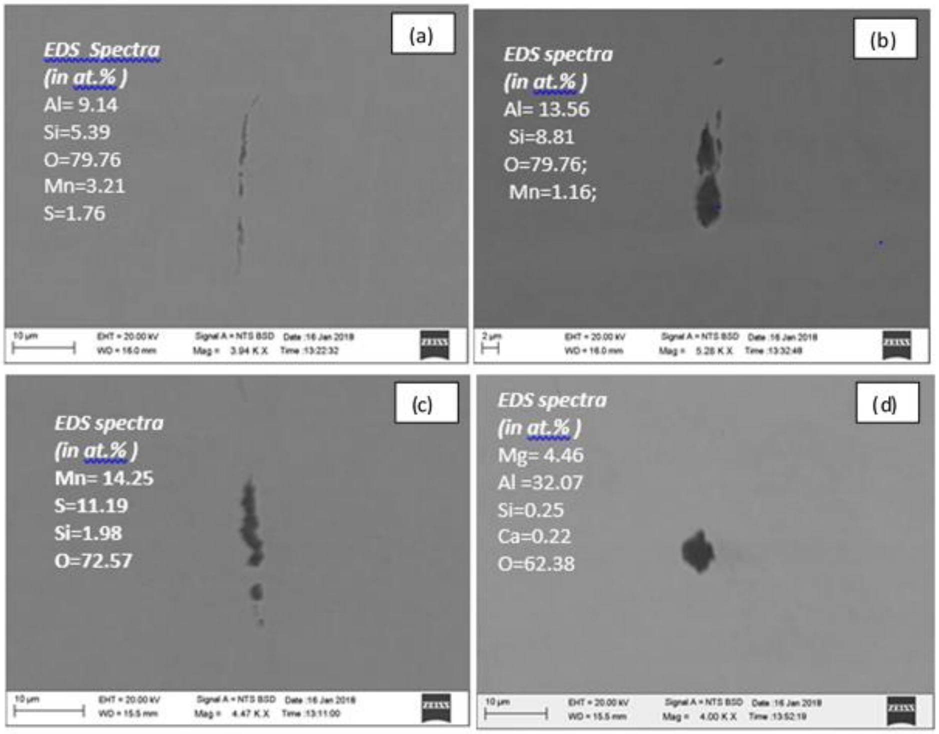


Fig.10 The type of alumina silicate inclusions and their association with sulphides (a) Predominantly $Al_2O_3.SiO_2$ inclusion associated with minor MnS inclusion (b) Al_2O_3-SiO_2-MnO type inclusion (c) SiO_2 inclusion associated with MnS (d) A non deformable MgO-Al_2O_3 type inclusion with minor association of Si and Al.

Non-metallic oxide inclusions form the next detrimental phase in the wire rod steel that affects the wire drawing operation. In the present study, the inclusions identified in the wire rod products were $Al_2O_3.SiO_2$ inclusion associated with minor MnS inclusion, Al_2O_3-SiO_2-MnO type inclusion, SiO_2 inclusion associated with MnS and a non- deformable MgO-Al_2O_3 type inclusion with minor association of Si and Al. Usually, the high carbon wire rod steel is Si-Mn deoxidised and hence, there remains non-metallic inclusions of MnO-SiO_2 type. These inclusions are required to be less than 15 microns and in the actual examination this is < 10 microns. The MnO-SiO_2 inclusions analysis was confirmed by SEM-EDS as shown in Fig.10. It is also noticed that there could be some amount of TiN type inclusion in the wire rod products Fig.11. These inclusions are detrimental as they nucleate cracks easily during subsequent wire drawing operations.

Fig. 11 SEM micrograph of the TiN inclusion and EDS analysis

4.0 Conclusion

In the production of high carbon wire rods with cross section between 5.5 and 13mm, the influence of carbon content and diameter on the tensile strength and reduction in area in the as-hot rolled condition was examined using the industrial production data. The tensile strength was found to increase and ductility [%RA] decreased, with increasing carbon content due to increased pearlite volume fraction. With increasing diameter of the wire rod the tensile strength and ductility was found to decrease associated with the coarseness of pearlite in bigger diameter wire rods. The detrimental phases in the steel can affect the mechanical properties and performance of the steel. These include, isolated martensite phase, grain boundary cementite, TiN inclusion. The steel forms MnO-SiO_2 type deformable inclusions which could be tolerated in the wire rod manufacture. Microstructural correlations could be obtained on the above mentioned aspects.

Acknowledgement

The authors wish to thank the JSW Steel management for the support given for this study.

REFERENCES

1. M. Kazeminezhad and A.K. Taheri, The effect of controlled cooling after hot rolling on the mechanical properties of a commercial high carbon steel wire rod,*Materials and Design, 2003, 24(6), 415-421*.

2. T. Gladman, I.D. McIvor, F.B. Pickering, Some aspects of the structure-property relationships inhigh-C ferrite-pearlite steels,*Journal of Iron and Steel Instititute,1972, 210(12), 916-930.*

3. P.C. Campbell, E.B. Hawbolt and J.KBrimacombe, Microstructural engineering applied to the controlled cooling of steel wire rod: Part II. Microstructural evolution and mechanical properties correlations. *Metallurgical and Materials Transactions A, 1991 22(11):2779-2790.*

4. O.P. Modi,N Deshmukh,D.P. Mondal et al., Effect of interlamellar spacing on the mechanical properties of 0.65% C steel, *Material Characterization,2001, 46(5), 347-352.*

5. E. M. Taleff, J Lewandowski, B. Pourladian. Microstructure-property relationships in pearlitic eutectoid and hypereutectoid carbon steels,*Journal of Materials, 2002, 54(7), 25-30.*

6. A. M. Elwazri, P. Wanjara andS. Yue, The effect of microstructural characteristics of pearlite on the mechanical properties of hypereutectoid steel,*Material Science and Engineering A, 2005, 404(1), 91-98.*

7. G. Langford, Deformation of pearlite. *Metallurgical and Materials Transactions A, 1977, 8(6), 861-875.*

8.K. Strecken,M Pfennig and E Anelli, Optimizing the structure of high carbon steel wire. *Brussels. European commission, 1998, EUR 18434*

9. C.M. Bae, W. L. Nam and C.S. Lee, Effect of interlamellar spacing on the delamination of pearlitic steel wires. *Scriptamaterialia, 1996 35(5), 641-646.*

10. J.M. Hyzak andI. M. Bernstein, The role of microstructure on the strength and toughness of fully pearlitic steels. *Metallurgical and Materials Transactions A, 1976, 7(8),1217-1224.*

11. S. B. Fabio da,*Characterization of the pro-eutectoid cementite network observed I the SAE 1092 wire rod steel grade*, master's thesis, Pittsburgh PA, University of Pittsburgh,2004.

12. W. H. Yu, L Liu, YXia et al., The effect of vanadium on the phase transformation of the 82B steel,*Journal of Metallurgical Engineering, 2013, 2(4), 140-148.*

13. K Kirihara, Production technology of wire rod for high tensile strength steel cord. *Kobelco Technology Review. 2011 30: 62.*

14. E. Anelii, I. Rodriguez, K. Stercken, M. Thiele M, H. A. Schifferi H A and K Haberz, "New steel generation for high strength large diameter wire rods", *European Commission Technical Research.2002. EUR 20195*.

15. J.Wang, P.J. Van Der Wolk andS. Van Der Zwaag, Effects of carbon concentration and cooling rate on continuous cooling transformations predicted by artificial neural network,*Iron and Steel Institute of Japan. 1999, 39(10), 1038-1046.*

16.H. C.Choi and K.T. Park, The effect of carbon content on the Hall-Petch parameter in the cold drawn hypereutectoid steels. *Scriptamaterialia, 1996, 34(6), 857-862.*

17. C Shuwei,*Development of 72A High Carbon Wire Rod for Bead Wire. 2016*

18. http://britishsteel.co.uk/media/40485/tyre-cord-datasheet.pdf