Intercritical Heat Treatments and the Mechanical Properties of Hot-Rolled Low Carbon Steels.

P.O. Offor, M.Eng[1] and B.A. Ezekoye, Ph.D.[2*]

[1]Department of Metallurgical and Materials Engineering, University of Nigeria, Nsukka, Nigeria.
[2]Solid-State and Material Science Division, Department of Physics and Astronomy, University of Nigeria, Nsukka, Nigeria.

[1]E-mail: peterjoyoffor@yahoo.com
[2*]E-mail: bezekoye@yahoo.com

ABSTRACT

Studies were carried out to determine the diverse effect of intercritical treatments on the mechanical properties of some low carbon steels. Six samples of the low carbon steels containing carbon in the range, 0.13 to 0. 18 wt%, were studied. After intercritical quenching, with or without low temperature tempering, intercritical annealing and intercritical normalizing, the properties of the samples were determined. The intercritical and tempering temperatures were 740^0C and 180^0C, respectively.

The mechanical properties of the heat treated and the non-heat treated specimens were obtained and compared. The results revealed that intercritical quenching, with or without low temperature tempering, increased the tensile strength and hardness of the samples but decreased their ductility and toughness. Normalizing increased ductility and toughness, but reduced strength and hardness; while annealing reduced all the properties studied.

(Keywords: intercritical temperature, quenching, tempering, annealing, normalizing, mechanical properties)

INTRODUCTION

The microstructure and mechanical properties of martensitic–ferritic dual–phase steels have become widely studied [1-7]. It has been shown that the dual-phase steels had better formabilities than conventional steels, and this included of their enhanced uniform elongation to necking [3]. These steels are generally characterized by continuous yielding behavior at low yield strength, a high tensile strength, high total and uniform elongation values and a high strain.

The cost advantages vary with the end product, in general, their high strengths allow a reduction on the thickness of engineering parts, enabling the user to purchase lower tonnages, and this more than compensates for their additional unit costs. High strength steels can also make a substantial contribution to energy efficiency [8].

In general, the major features controlling the mechanical properties of ferrite–peartite, pearlite, and austenitic structures are reasonably well understood and quantified [9], recent work generally being concerned with defining predictive capabilities of fairly well established relationships. An interesting emphasis has been shown for the effect of carbide particle size or pearlitic cementite lamella thickness on toughness, particularly the ductile–brittle transition temperature, and this is associated with the micro mechanism of the fracture process [9].

The actual factors which control the properties of steels are structural, and in carbon steels these consist of ferrite grain size, the proportion of pearlite in the structure, the pearlite spacing, and solid solution hardening and precipitation effects [9,10]. The purpose of this work was to investigate the effect of diverse heat treatments on the mechanical properties of the six low carbon steels, containing carbon with the range 0.13 to 0.18 wt %C. The samples for this study include tensile and notch impact specimens which were obtained from hot-rolled steel rods, 16 mm diameter with chemical compositions given in Table 1.

Table 1: Chemical Compositions (wt %) of Steels Used, with their Critical Temperatures (calculated).

Steel	C	Si	Mn	P	S	Cr	Nr	Sn	Mu	Al	Cu	V	N	AC1 ^{0}C	AC3 ^{0}C
A	0.150	0.250	0.640	0.013	0.021	0.060	0.060	0.009	0.020	0.003	0.130	0.001	0.008	723	830
B	0.140	0.190	0.450	0.078	0.014	0.003	0.004	0.001	0.010	-	0.040	0.002	0.004	723	882
C	0.130	0.120	0.470	0.034	0.009	-	-	-	0.002	0.010	0.020	0.002	0.004	721	853
D	0.0160	0.090	0.450	0.013	0.007	-	0.003	0.001	0.005	-	0.040	0.001	0.004	721	828
E	0.170	0.150	0.590	0.018	0.007	0.020	0.010	0.001	0.004	0.004	0.040	0.001	0.005	721	829
F	0.180	0.130	0.520	0.150	0.008	0.030	0.020	0.003	0.010	0.003	0.060	0.001	0.006	721	824

MATERIALS AND METHODS

The test samples used for the present work were machined from the steel rods to specifications. The samples were subjected to various tests after treatments in order to determine their mechanical properties

Methods: Test specimens were heat treated in series according to the following heat treatment schedules:

Series 1. Intercritical quench: The specimens were held for 1hr at 740^{0}C cold water quenched;

Series II. Intercritical quench–temper: the specimens were held for 1hr at 740^{0}C; cold water quenched; 1hr temper at 180^{0}C; air cool.;

Series III Intercritical anneal: the specimens were held for 1hr at 740^{0}C; furnace cool;

Series IV Intercritical normalize: the specimens were held for 1hr at 740^{0}C; air cool;

Series V. Non-heat treated as received hot-rolled specimens.

The specimens were subjected to tensile, hardness and impact test. Some sample specimens of steel D were selected for optical metallographic studies.

RESULTS AND DISCUSSION

The results of the various measurements are tabulated in Tables 2 through 6.

The effects of the intercritical heat treatments on the mechanical properties of the as hot – rolled specimens are summarized in tables 7(a) through 7(f).

The positive values in table 7(a) through 7(f) show by how much the value of the mechanical properties of the heat treated specimens were above those of hot – rolled specimens.

Table 2: Intercritical Quenching (Series I).

Steel	σ y (N/mm^2)	σ t (N/mm^2)	σ y/ σ t	φ (%)	δ (%)	H HB	an (J/cm^2)
A	-	576.94	-	59.12	14.00	197	3.57
B	-	581.34	-	42.24	3.53	187	3.65
C	-	835.56	-	9.39	2.98	285	15.00
D	-	517.21	-	59.28	6.44	209	6.25
E	-	701.28	-	12.34	5.73	229	3.89
F	-	676.40	-	20.12	4.35	241	2.72

Table 3: Intercritical Quenching and Tempering (Series II).

Steel	σ y N/mm^2	σ t N/mm^2	σ y/ σ t	φ %	δ %	H HB	an J/cm^2
A	308.36	447.62	0.689	70.64	11.69	163	13.99
B	382.97	586.88	0.653	03.10	10.19	137	62.05
C	-	651.54	-	45.33	4.75	197	71.95
D	-	462.54	-	66.29	7.69	170	80.93
E	-	576.94	-	58.72	1.63	197	46.39
F	-	616.73	-	51.61	2.60	207	24.45

Table 4: Intercritical Annealing (Series III).

Steel	σ y N/mm^2	σ t N/mm^2	σ y/ σ t	φ %	δ %	H HB	an J/cm^2
A	288.47	417.78	0.690	69.20	22.56	137	106.32
B	288.47	427.43	0.675	65.18	31.81	121	66.88
C	258.63	363.07	0.772	67.44	39.94	143	84.03
D	233.16	343.17	0.681	49.41	39.40	137	58.86
E	263.60	392.91	0.671	62.48	38.81	143	117.26
F	279.52	397.89	0.700	64.52	34.85	149	81.40

Table 5: Intercritical Normalizing (Series IV).

Steel	σ y N/mm^2	σ t N/mm^2	σ y/ σ t	φ %	δ %	H HB	an J/cm^2
A	318.31	457.57	0.696	6892	37.09	157	107.23
B	318.31	462.54	0.688	98.28	36.78	137	68.59
C	158.63	387.54	0.667	69.82	37.88	126	92.90
D	253.65	377.99	0.671	54.94	40.56	149	138.33
E	293.44	427.73	0.686	63.02	3798	156	131.71
F	293.44	427.73	0.686	62.23	39.73	163	143.97

Table 6: Non-Heat Treated as Hot Rolled Specimens (Series V).

Steel	σy N/mm^2	σt N/mm^2	σ y/ σ t	φ %	δ	H HB	an J/cm^2
A	318.34	452.60	0.703	68.29	37.25	143	83.93
B	318.31	457.52	0.689	67.79	37.34	187	70.31
C	268.57	397.89	0.675	64.22	36.84	131	91.67
D	273.55	387.94	0.705	71.18	28.96	156	89.04
E	298.42	432.70	0.690	65.50	38.56	163	90.00
F	298.42	437.68	0.682	67.08	38.25	170	60.05

Table 7: Steel Properties and Treatments.

Table 7 (a): Steel A. (Q= Quench in water; A$ = Air cooled; Fc = Furnace cooled)

Series	$\triangle\sigma$ y (N/mm^2)	$\triangle\sigma$ t (N/mm^2)	$\triangle\sigma$ y/ σ t	$\triangle\varphi$ (%)	$\triangle\delta$ (%)	$\triangle$ H (HB)	$\triangle$ an (J/cm^2)	Heat Treatment Temp. (^{O}C)
I	318.31	123.34	-0.703	-9.17	-23.25	54	-80.36	740Q
II	-9.95	-4.98	-0.014	2.35	-25.56	20	-69.94	740Q+180A$^{\$}$
III	-29.84	-38.82	0.013	0.91	-14.69	-6	22.30	740Fc
IV	0	4.97	0.007	0.63	-0.16	14	23.30	740A$^{\$}$

Table 7 (b): Steel B. (Q =Quench in water; A$ = Air cooled; Fc = Furnace cooled)

Series	$\triangle\sigma$ y (N/mm^2)	$\triangle\sigma$ t (N/mm^2)	$\triangle\sigma$ y/ σ t	$\triangle\varphi$ (%)	$\triangle\delta$ (%)	$\triangle$ H (HB)	$\triangle$ an (J/cm^2)	Heat Treatment Temp. (^{O}C)
I	318.31	213.82	-0.681	25.55	-33.81	50	-66.66	740Q
II	64.66	119.36	0.028	-4.69	-27.15	0	-8.26	740Q+180$^{\$}$
III	-29.84	-0.09	-0.006	2.61	-5.53	-16	-3.43	740Fc
IV	0	-4.98	0.007	8.51	8.56	0	-1.72	740A$^{\$}$

Table 7 (c): Steel C. (Quench in water; A$ = Air cooled; Fc = Furnace cooled)

Series	$\triangle\sigma$ y (N/mm^2)	$\triangle\sigma$ t (N/mm^2)	$\triangle\sigma$ y/ σ t	$\triangle\varphi$ (%)	$\triangle\delta$ (%)	$\triangle$ H (HB)	$\triangle$ an (J/cm^2)	Heat Treatment Temp. (^{O}C)
I	-268.57	437.67	-0.675	-54.83	-33.86	154	-76.67	740Q
II	-268.57	253.65	0.675	18.00	32.00	00	-19.72	740Q+180A$^{\$}$
III	-9.94	-34.82	0.037	3.22	3.10	12	-7.59	740F c
IV	-9.94	-10.35	-0.008	5.00	1.04	5	1.23	740A$^{\$}$

Table 7 (d): Steel D. (Quench in water; A$ = Air cooled; Fc = Furnace cooled)

Series	$\Delta\sigma$ y (N/mm^2)	$\Delta\sigma$ t (N/mm^2)	$\Delta\sigma$ y/ σ t	$\Delta\varphi$ (%)	$\Delta\delta$ (%)	Δ H (HB)	Δ an (J/cm^2)	Heat Treatment Temp. (^{O}C)
I	-273. 55	129.27	-0.705	-11.90	-22.52	53	-82.79	740Q
II	-273.55	24.60	-0.105	4.00	-21 27	14	-8.11	740Q+180A$^{\$}$
III	-39.79	-44.77	-0.024	-21.77	10.44	-19	-30.81	740Fc
IV	19.90	10.15	-0.034	-16.24	11.56	-7	49.29	740A$^{\$}$

Table 7 (e): Steel E. (Quench in water; A$ = Air cooled; Fc = Furnace cooled)

Series	$\Delta\sigma$ y (N/mm^2)	$\Delta\sigma$ t (N/mm^2)	$\Delta\sigma$ y/ σ t	$\Delta\varphi$ (%)	$\Delta\delta$ (%)	Δ H (HB)	Δ an (J/cm^2)	Heat Treatment Temp. (^{O}C)
I	-298.42	268.58	-0.690	53.44	-32.83	66	-86.11	740Q
II	-298.42	144.24	-0.690	-7.06	-36.93	34	-43.61	740Q+180A$^{\$}$
III	-43.82	-39.79	0.019	-3.30	0.25	-20	27.26	740Fc
IV	-4.97	-497	0.004	-2.76	0.58	-7	41.71	740A$^{\$}$

Table 7 (f): Steel F. (Quench in water; A$ = Air cooled; Fc = Furnace cooled)

Series	$\Delta\sigma$ y (N/mm^2)	$\Delta\sigma$ t (N/mm^2)	$\Delta\sigma$ y/ σ t	$\Delta\varphi$ (%)	$\Delta\delta$ (%)	Δ H (HB)	Δ an (J/cm^2)	Heat Treatment Temp. (^{O}C)
I	298.42	238.72	-6.682	-46.96	-33.90	71	-51.33	740Q
II	-298.42	179.05	-0.682	-1547	35.65	37	-35.60	740Q+180A$
III	-19,90	-39.79	-0.018	-2.56	-3.40	-21	21.35	740Fc
IV	-4.90	-9.95	0.004	4.85	1.48	-7	83.92	740A$

On the other hand the negative values in tables 7(a) through 7(f) show by how much the value of the mechanical properties of the heat treated specimens were below those of the non- heat treated as hot-rolled specimens.

The initial microstructure of the steels consisted of banded ferrite-pearlite structure of the non-heat treated as hot-rolled specimen (Figure 1).

The photomicrographs of the steel after intercritical quenching and intercritical quenching plus low temperature tempering are shown in Figure 2. The average grain sizes on the photomicrographs are 3.71 x 10^{-3} cm and 2.88 x 10^{-3} cm, respectively. The volume fractions of the martensites are 40% and 52%, respectively. Here, the martensite islands are randomly distributed in ferrite matrix but have appreciably larger dimensions in directions along prior austenite grain boundaries. In Figure 2 the dark areas are martensite islands.

The photomicrographs of the steel after intercritical annealing and intercritical normalizing are shown in Figure3. The average grain sizes on the photomicrographs are 4.02 x 10^{-3}cm and 3.45 x 10^{-3}cm respectively. The volume fractions of pearlite are 46% and 38 % respectively. Here, banding structures of ferrite – pearlite structures developed.

Figure 1: (Series V) The Microstructure of as Hot Rolled Steel D rod, Ferrite-Pearlite Structure (x200).

Figure 2a: (Series 1) The Microstructure of Steel D rod after Intercritical Quenching at 740^{o}C Ferrite-Martensite Structure (x200).

Figure 2b: (Series II) The Microstructure of Steel D rod after Intercritical Quenching at 740^{o}C plus Low Temperature Tempering at 180^{o}C Ferrite-Martensite (x200).

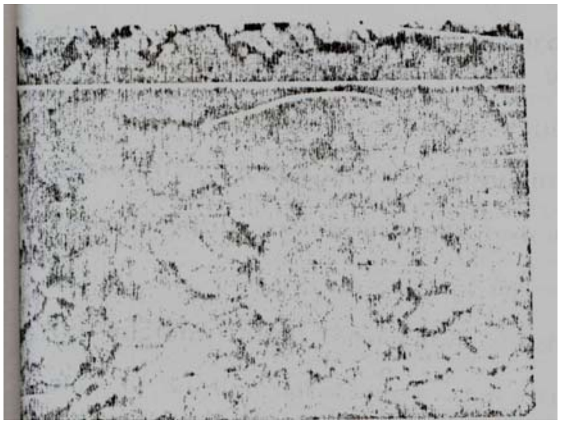

Figure 3a: (Series III) The Microstructure of Steel rod after Intercritical Annealing at 740^{o}C Ferrite-Pearlite Structure (x200).

Figure 3b: (Series IV) The Microstructure of Steel rod after Intercritical Normalizing at 740^{o}C Ferrite-Pearlite Structure (x200).

CONCLUSIONS

The intercritical heat treatments on low carbon steels, with or without low temperature tempering, intercritical annealing, and intercritical normalizing at intercritical and tempering temperatures of 740^{0}C and 180^{0}C, respectively, affected the mechanical properties of the steel samples studied.

The investigations carried out on the steel samples revealed the following: 1) intercritical normalizing produced the best notch impact toughness compared with all the heat treatment procedures adopted; 2) intercritical quenching and intercritical quenching plus low temperature tempering showed no yield strength values; 3) intercritical quenching and intercritical quenching plus low temperature tempering increased the ultimate tensile strength and hardness properties but reduced tensile ductility and notch impact toughness properties; 4) intercritical annealing reduced the yield strength, ultimate tensile strength, tensile ductility, hardness and notch impact toughness properties; and 5) intercritical normalizing increased the tensile ductility and notch impact toughness properties but reduced the yield strength, ultimate tensile strength and hardness properties.

REFERENCES

1. Lenel, U.R. and R.W.K. Honeycombe. 1984. “Morphology and Crystallography of Austenite formed during Intercritical Annealing”. *Metal Science*.18:503-510.
2. Yi, J.J. et al. 1985. “Austenitization during Intercritical Annealing of Fe – C – Si – Mn – Dual-Phase Steel”. *Metallurgical Transactions A*. 16A:985 – 1237.
3. Lei, T.C. et al. 1985 “Microstructure and Tensile Properties of Intercritically Quenched 0.3C – Cr – Mn - Si Steel”. *Material Science and Technology*. 1:104 – 110.
4. Chuanya, W. 1984. “The Structure and Properties of High Strength Sheet Steel 16 Mn Steel after IHT (Intercritical Heat Treatment.” *Proceedings of Heat Treatment*.
5. Cai, X. 1985 “The Dependence of some Tensile and Fatigue Properties of a Dual – Phase Steel on its Microstructure”. *Metallurgical Transactions A*. 16A:1405 – 1415.
6. Offor, P.O. 1993 “The Effect of Diverse Heat Treatment on the Mechanical Properties of Structural Steels”. Unpublished M.Eng. Thesis.
7. Leslie, W.C. 1983. *The Physical Metallurgy of Steels*. McGraw-Hill, International: New York, NY. 219-257.
8. Choudary, R.B. 2003. *Material Science and Metallurgy.* Khanna Publishers: Delhi, India. 306 – 355.
9. Pickering, F.B. 1981. “Ferrous Physical Metallurgy some Achievements and Application.” *Proceedings of the Metals Society.* University of Liverpool conference on Advances in Physical Metallurgy and Applications of Steels. 5 – 25.
10. Dieter, G.E. 1987. *Mechanical Metallurgy*. McGraw-Hill, International: New York, NY. 227.

ABOUT THE AUTHORS

Peter O. Offor, M. Eng., is a Faculty member of the Faculty of Engineering, University of Nigeria, Nsukka, Nigeria. He is currently lecturing in the Department of Metallurgical and Materials Engineering of the University. His research interests include physical metallurgy, thin films growth and characterizations, nanosciences and nanotechnology.

Benjamin A. Ezekoye, Ph.D., MSESN, MNIP, is a Faculty member of the Faculty of Physical Sciences, University of Nigeria, Nsukka, Nigeria. He has numerous scientific publications in renowned local and international journals. He is currently lecturing in Department of Physics and Astronomy, Solid-State, and Material Science Division, of the University. His research interests include thin solid films growth and characterizations, nanosciences, nanotechnology, polymer materials, and solar energy.

SUGGESTED CITATION

Offor, P.O. and B.A. Ezekoye. 2009. “Intercritical Heat Treatments and the Mechanical Properties of Hot-Rolled Low Carbon Steels”. *Pacific Journal of Science and Technology.* 10(2):142-148.

Pacific Journal of Science and Technology