INTERCRITICAL HEAT TREATMENT EFFECTS ON LOW CARBON STEELS QUENCHED FROM INTERMEDIATE TEMPERATURE AUSTENITIZATION

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ABSTRACT

Six low carbon steels containing carbon in the range 0.13-0.18wt%C were studied after intercritical quenching, intercritical quenching with low temperature tempering, intercritical annealing and intercritical normalizing using specimens originally quenched from intermediate austenitizing temperature (950^{0}C). The studies also examined the microstructure of the intermediate austenitizing temperature (950^{0}C) quenched specimens. The intercritical and tempering temperatures were 740^{0}C and 180^{0}C respectively. Comparison of the mechanical properties of the intercritically heat treated specimens with those of the intermediate austenitizing temperature specimens showed that intercritical quenching with low temperature tempering reduced the ultimate tensile strength and hardness and increased the percentage reduction in area and the notch impact toughness. Intercritical annealing and intercritical normalizing increased the yield strength, ductility and toughness but decreased the ultimate tensile strength and hardness.

Keywords: Mechanical properties, intercritical heat-treatments, austenitizing temperature, intermediate temperature.

Symbols Used: σ_y = Yield strength; σ_t = Ultimate tensile strength; $\frac{\sigma_y}{\sigma_t}$ = Yield/Ultimate Strength Ratio; φ = Percentage Reduction in Area; δ = Percentage Elongation; H = Hardness; an = Notch Impact Toughness; Δ = Change in.

1.0 INTRODUCTION

The need for lower automobile vehicle weights and the resultant improvement in the fuel economy particularly in the United States of America has resulted in the development of steels with increased strength/weight ratios. For example, it has been reported that decreasing an average car weight from 1750 kg to 1500 kg can improve the fuel consumption by up to 2 km/litre. The high strength micro-alloyed steels, however, suffer from the disadvantage that they show lower formability compared with conventional low-carbon steels, which can necessitate a redesign of components and forming equipments. To overcome this disadvantage, dual-phase steel were developed which combined the conflicting requirements of high strength and improved formability [1].

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, solid solution hardening and precipitation effects [2]. Of all the metallic materials of engineering importance, none exhibit a wider variety of microstructure, and hence of available or potential mechanical properties, than do steel [3].

Several attempts have been made to describe the deformation behaviour and structure-property relationships of dual-phase steels [1, 4-6], often by using models based on composite materials [1]. Many of these attempts start with the same basic assumption of a duplex structure comprising hard particles embedded in a soft ferrite matrix, but then differ in the way the strain is partitioned between the phases. The purpose of this work was to investigate the effect of diverse intercritical heat treatments on the mechanical properties of six low carbon steels, containing carbon with the range 0.13 to 0.18 wt %C originally quenched from intermediate austenitization temperature (950^{0}C).

2.0 MATERIALS AND METHODS.

2.1 Materials

The specimens for the experiments comprised of tensile and notch impact specimens which were obtained from hot rolled 16mm diameter rods with chemical compositions given in table 1. The test specimens were machined from the rods to ASTM specification [7] and tested after treatments.

Table 1: Chemical Compositions (wt%) and Critical Temperatures of Steel Samples.

Steel	A	B	C	D	E	F
Carbon C	0.150	0.140	0.130	0.160	0.170	0.180
Silicon Si	0.250	0.190	0.120	0.090	0.150	0.130
Manganese Mn	0.640	0.450	0.470	0.450	0.490	0.520
Phosphorus P	0.013	0.078	0.034	0.013	0.018	0.150
Sulphur S	0.021	0.014	0.009	0.007	0.007	0.008
Chromium Cr	0.060	0.003	-	-	0.002	0.003
Nickel Ni	0.060	0.004	-	0.003	0.010	0.020
Tin Sn	0.009	0.001	-	0.001	0.001	0.003
Molybdenum Mo	0.020	0.010	0.002	0.005	0.004	0.010
Aluminum Al	0.003	-	0.010	-	0.004	0.003
Copper Cu	0.130	0.040	0.020	0.040	0.040	0.060
Vanadium V	0.001	0.002	0.002	0.001	0.001	0.001
Nitrogen N	0.008	0.004	0.004	0.004	0.005	0.006
AC_1/^{o}C	723	723	721	721	721	721
AC_3/^{o}C	830	882	853	828	829	824

2.2 Methods

The test specimens were heat treated in series using a heat treatment furnace according to the following heat treatment schedules:

Series I- Prequench: The specimens were held at 950^0 C for 1 hour; cold water quenched; held at 740^{0}C for 1hour; cold water quenched;

Series II- Intercritical quench with prequench: the specimens were held at 950^0C for 1 hour; cold water quenched;

Series III- Intercritical quench temper with prequenching: the specimens were held at 950^0 for 1hour; cold water quenched; held at 740^0C for 1hour; cold water quenched tempered at 180^0C for 1hour; air cooled.;

Series IV- intercritical anneal with prequench: the specimens were held at 950^0C for 1hour; cold water quenched; held at 740^0C for 1hour; furnace cooled.

Series V- Intercritical normalize with prequench: The specimens were held at 950^0C for 1hour; cold water quenched; held at 740^0C for 1hour; air cooled. The heat-treated samples were subjected to tensile test using a ten ton universal testing machine, using Brinell's hardness test method and notch impact toughness test using Charpy impact test method. Some specimens of steel D were picked for optical metallographic studies. To ensure appropriate choice of temperature, the critical temperatures AC_1 and AC_3 were initially estimated from equations developed by Andrews [8].

3.0 RESULTS AND DISCUSSION

The experimental results are tabulated as shown in tables (1 – 6).

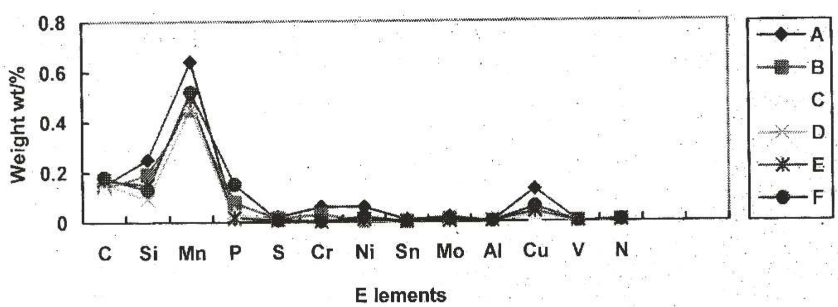

Fig. 1: Chemical Compositions (wt%) Steel Samples

Table 2: Cold Water Quenching after Intermediate Austenitizing Temperature (Series I)

Steel sample	A	B	C	D	E	F
σ_y /N/mm^2	-	-	-	-		-
σ_t /N/mm^2	596.83	706.25	576.94	532.17	611.75	1039.48
σ_y / σ_t	-	-	-	-		-
φ /%	66.79	64.75	63.77	58.96	55.03	26.15
δ /%	4.29	19.50	14.54	19.71	4.43	6.06
H/BHN	255	229	229	255	269	321
an/J/cm^2	17.86	27.98	113.24	27.50	17.76	53.19

Table 3: Intercritical Quenching after Intermediate Austenitizing Temperature

Prequenching (Series II).

Steel sample	A	B	C	D	E	F
σ_y /N/mm^2	-	-	-	-		-
σ_t /N/mm^2	646.57	586.88	566.89	527.20	576.94	601.80
σ_y / σ_t	-	-	-	-		-
φ /%	49.86	60.26	52.39	66.07	66.58	47.71
δ /%	12.29	3.60	22.25	18.66	16.98	21.10
H/HB	187	170	197	197	217	229
an/J/cm^2	17.26	23.68	12.84	17.19	18.97	13.54

Table 4: Intercritical Quenching and Tempering after Intermediate Austenitizing Temperature Prequenching (Series III).

Steel sample	A	B	C	D	E	F
σ_y /N/mm^2	-	-	-	-	-	-
σ_t /N/mm^2	452.60	517.25	557.04	477.46	527.20	542.12
σ_y / σ_t	-	-	-	-	-	-
φ /%	71.31	64.75	64.82	69.41	61.33	56.27
δ /%	10.96	0.46	23.71	13.39	18.11	15.41
H/HB	149	156	152	176	187	207
an/J/cm^2	36.06	82.93	83.65	56.67	92.47	39.16

Table 5: Intercitical Annealing after Intermediate Temperature Austenitization Prequenching (Series IV)

Steel sample	A	B	C	D	E	F
σ_y /N/mm^2	263.60	278.52	208.89	233.76	273.55	268.57
σ_t /N/mm^2	397.89	407.83	333.23	333.23	377.99	382.97
σ_y / σ_t	0.662	0.683	0.627	0.701	0.724	0.701
φ /%	68.43	65.56	68.57	67.44	65.56	64.84
δ /%	35.03	33.04	31.88	38.28	3781	37.44
H/HB	143	121	105	137	126	143

Table 6: Intercritical Normalizing after IntermediateTemperature Austenitization Prequenching (Series V)

Steel sample	A	B	C	D	E	F
σ_y /N/mm^2	308.36	298.42	248.64	258.63	303.39	303.39
σ_t /N/mm^2	452.60	44.62	373.02	373.02	422.76	432.70
σ_y / σ_t	0.681	0.667	0.667	0.693	0.718	0.701
φ /%	66.94	60.31	67.84	67.30	64.75	63.77
δ /%	34.60	28.38	33.49	32.00	35.84	35.50
H/HB	152	137	126	146	156	163
an/J/cm^2	95.51	82.31	87.21	107.78	139.39	93.68

The effects of intercritical heat treatments on the mechanical properties of specimens quenched from intermediate temperature austenitization (950^{O}C) are summarized in tables 7(a)-7(f). The positive values in tables 7(a)-7(f) show by how much the values of the mechanical properties of the intercritically heat treated specimens were above those of the intermediate temperature autenitization prequenched specimens. On the other hand the negative values show by how much the values of the mechanical properties of the intercritically heat treated specimens were below those of the intermediate temperature austenitization prequenched specimens.

The initial microstructure of the specimens that were intercritically heat treated consisted of specimen's prequenched from intermediate temperature austenitization (950^{0}C) to gain non-equilibrium original martensite structure. The average grain size on the photomicrograph is 5.97 × 10^{-3} cm (see Fig. 1). The photomicrographs of the steel after prequenching from the intermediate temperature austenitization (950^{0}C) followed by intercritical quenching and by intercritical quenching with low temperature tempering are shown in (Figs. 2a & 2b) respectively.

The average grain sizes on the photomicrographs are 3.1 × 10^{-3}cm and 3.5 × 10^{-3}cm respectively. The volume fractions of the martensite are 57% and 59% respectively.

Table 7(a): Effects of intercritical heat treatments on mechanical properties (Steel A)

Steel sample	II	III	IV	V
$\Delta\sigma_y$ /N/mm^2	-	-	263.60	308.36
$\Delta\sigma_t$ /N/mm^2	49.74	-144.23	-198.94	-144.23
$\Delta(\sigma_y / \sigma_t)$	-	-	0.66	0.16
Δφ /%	-16.92	14.53	1.65	0.16
Δδ /%	8.00	0.75	30.74	30.31
ΔH/HB	-72	-106	-112	-103
Δ an/J/cm^2	-0.60	18.20	70.38	77.65
Heat TreatmentTemps/°C	950Q	950Q+740Q+180A$^\$$	950Q+740FC	950Q+740A$^\$$

(Q=Quench in water; A$^{\$}$ = Air cooled ; Fc = Furnace cooled).

Table 7(b): Effects of intercritical heat treatments on mechanical properties (Steel B)

Steel sample	II	III	IV	V
$\Delta\sigma_y$ /N/mm^2	-	-	278.52	298.42
$\Delta\sigma_t$ /N/mm^2	5.57	-64.06	-173.48	-133.69
$\Delta(\sigma_y / \sigma_t)$	-	-	0.683	0.667
$\Delta\varphi$ /%	-4.49	0	0.81	-4.44
$\Delta\delta$ /%	-15.90	-19.04	13.54	8.88
ΔH/HB	-59	-73	-108	-90
Δ an/J/cm^2	-4.30	54.95	47.60	54.33
Heat Treatment Temps/°C	950Q + 740Q	950Q + 740Q + 180A$^\$$	950Q +740Fc	950Q + 740A$^\$$

(Q=Quench in water; A$^{\$=}$ Air cooled; Fc=Furnace cooled).

Table 7(c): Effects of intercritical heat treatments on mechanical properties (Steel C)

Steel sample	II	III	IV	V
$\Delta\sigma_y$ /N/mm^2	-	-	208.89	248.64
$\Delta\sigma_t$ /N/mm^2	99.47	29.84	-79.58	-39.59
$\Delta(\sigma_y / \sigma_t)$	-	-	0.625	0.667
$\Delta\varphi$ /%	-11.38	1.05	4.80	4.04
$\Delta\delta$ /%	7.71	9.17	17.34	18.95
ΔH/HB	-32	-77	-124	-103
Δ an/J/cm^2	-100.40	-29.59	2.09	-26.03
Heat Treatment Temps/°C	950Q + 740Q	950Q + 740Q + 18-A$^\$$	950Q + 740Fc	950Q + 740A$^\$$

(Q = Quench in water; A$^\$$ = Air cooled; Fc = Furnace cooled.)

Table 7(d): Effects of intercritical heat treatments on mechanical properties (Steel D)

Steel sample	II	III	IV	V
$\Delta\sigma_y$ /N/mm^2	-	-	233.76	258.63
$\Delta\sigma_t$ /N/mm^2	-4.97	-54.71	-198.94	-159.15
$\Delta(\sigma_y / \sigma_t)$	-	-	0.701	0.693
$\Delta\varphi$ /%	7.11	10.45	8.48	8.34
$\Delta\delta$ /%	-1.11	-6.32	18.57	12.20
ΔH/HB	-58	-76	-118	109
Δ an/J/cm^2	-10.31	29.17	-6.58	80.28
Heat Treatment Temps/°C	950Q + 740Q	950Q + 740Q + 180a$^\$$	950Q + 740Fc	950Q + 740A$^\$$

(Q = Quench in water; A$^\$$ = Air cooled; Fc = Furnace cooled.)

Table 7(e): Effects of intercritical heat treatments on mechanical properties (Steel E)

Steel sample	II	III	IV	V
$\Delta\sigma_y$ /N/mm^2	-	-	273.55	303.39
$\Delta\sigma_t$ /N/mm^2	-34.81	-84.55	-233.76	-188.99
$\Delta(\sigma_y / \sigma_t)$	-	-	0.724	0.718
$\Delta\varphi$ /%	10.5	6.30	11.53	9.72
$\Delta\delta$ /%	12.55	13.68	33.38	31.41
ΔH/HB	-52	-82	-143	-113
Δ an/J/cm^2	1.21	74.71	66.02	121.63
Heat Treatment Temps/°C	950Q + 740Q	950Q + 740Q + 180A$^\$$	950Q + 740Fc	950Q + 740A$^\$$

(Q =Quench in water; A$^\$$= Air cooled; Fc= Furnace cooled)

Table 7(f): Effects of intercritical heat treatments on mechanical properties (Steel E)

Steel Sample	II	III	IV	V
$\Delta\sigma_y$ /N/mm^2	-	-	268.57	303.39
$\Delta\sigma_t$ /N/mm^2	-437.68	-497.36	-656.51	-606.78
$\Delta(\sigma_y / \sigma_t)$	-	-	0.701	0.701
$\Delta\varphi$ /%	21.56	41.26	38.69	37.62
$\Delta\delta$ /%	15.04	9.35	31.38	29.4
ΔH/HB	-92	-114	-178	-158
Δ an/J/cm^2	39.65	-14.03	58.95	40.49
Heat Treatment Temps/°C	950Q + 740Q	950Q + 740Q + 180A$^\$$	950Q + 740Fc	950Q + 740A$^\$$

(Q = Quench in water; A$^\$$ = Air cooled; Fc = Furnace cooled).

Here, short packets of lamellarly arranged mixtures of martensite and ferrite needles (short acicular structure) are developed, the result of partially inherited lath martensite formed during the intermediate austenitization (950^{0}C) prequenching. The photomicrographs of the steel after prequenching from intermediate temperature austenitization (950^{0}C) followed by intercritical annealing and by intercritical normalizing are shown in (Fig. 3a & 3b) respectively. The average grain sizes of the photomicrographs are 4.11×10^{-3} cm and 3.31×10^{-3}cm respectively. The volume fractions of pearlite are 42% and 50% respectively. Here, banding structures of ferrite-pearlite structure with some acicular structures present were developed, the result of partially inherited lath martensite formed during the intermediate austenitization temperature (950^{0}C) prequenching. It was observed that strength and hardness increased with the severity of cooling from heat treatment temperature while ductility and hardness decreased. The observed mechanical properties follow the Hall-Petch equation; smaller grain size normally leads to increased yield strength

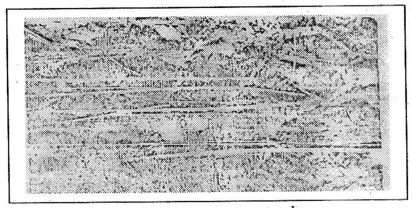

Fig. 1(Series I): The microstructure of steel D rod after intermediate temperature austenitization (950°C) prequench, martensite (200x).

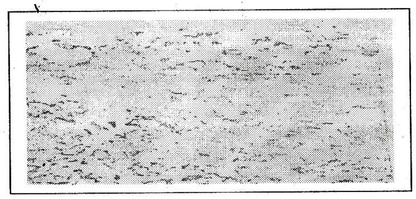

Fig. 2a (Series II): The microstructure of steel D rod after prequenching at 950°C followed by intercritical quenching at 740°C, short acicular ferrites-martensite structure (200x)

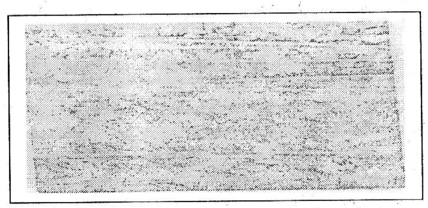

Fig. 2b (series III): The microstructure of steel D rod after prequenching at 950°C followed by intercritical quenching at 740°C plus low temperature tempering at 180°C, short acicular ferrite-martensite structure (200x)

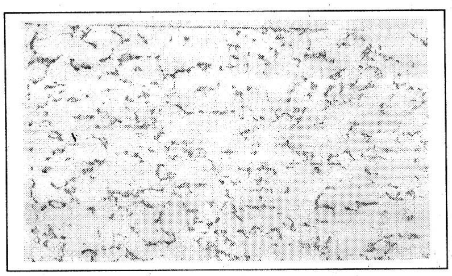

Fig. 3a (series IV): The microstructure of steel D rod after prequenching at 950°C followed by intercritical normalizing at 740°C, ferrite-pearlite structure (200x).

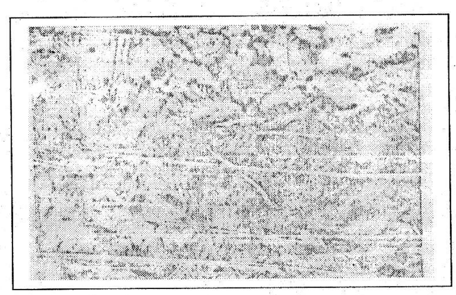

Fig. 3b (series V): The microstructure of steel D rod after prequenching at 950°C followed by intercritical annealing at 740°C, ferrite-pearlite structure (200x).

and impaired technological ductility of steel [8].

4.0 CONCLUSIONS

We successfully studied the effects of intercritical heat treatments on the mechanical properties of low carbon steels (carbon content, 0.13 - 0.18wt %) quenched from intermediate austenitization temperature, 950^{0}C. The intercritical and tempering temperatures were 740^{0}C and 180^{0}C respectively. The results revealed that the intercritically quenched and the intercritically quenched plus low temperature tempered specimen have no yield point values because of the high severity of quenching involved. Again, intercritical quenching plus low temperature tempering reduced the ultimate tensile strength and hardness properties and increased the percentage reduction of area and the notch impact toughness. Finally, intercritical annealing and intercritical normalizing increased the yield strength, elongation and reduction of area, and toughness but decreased the ultimate tensile strength and hardness properties.

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