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Research Article

Study of the Effect of Quenched and Inter Critical Heat Treatment on Mechanical Properties of Plain Low Carbon Steel (0.09% C, 0.5% Mn, 0.05% S)

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Abstract

Effect of quenched and inter critical heat treatment on structural steel (0.09 wt % C, 0.50 wt % Mn, 0.05 wt % S) has been investigated. Specimens for annealing, intercritical at two different temperatures and oil quenching were prepared. The heat treatment of the experimental steel was based on inter critical quenching in the ferrite plus austenite temperature range of the Fe–C phase diagram at temperatures 750⁰C and 850⁰C for 30 minutes at each temperature in a laboratory electric heat treatment furnace followed by quenching in plain water to room temperature. The results revealed that inter critical heat treatment optimized the yield strength, increased the tensile strength and hardness properties but decreased the ductility and notch impact toughness properties of the experimental steel. Moreover, the results also revealed that annealing eliminated the yield strength and produced a greater increase in tensile strength and decrease hardness properties but a greater increase in the ductility than oil quenching of the experimental steel.

Keywords: *DP steel, Heat treatment, Annealing, Quenching.*

1. Introduction

Plain carbon steels consisting of about four-fifths of the total tonnage of steel production, are economical compared to alloy steels. These are extensively used as structural components for many engineering applications. In recent years, the search and application of new advanced materials have been much in demand by the automotive industries. Approximately 85% of Advanced High Strength Steel (AHSS) should be used for different construction parts of a vehicle that could lead to a weight reduction up to 25% compared with a common model. The distinctly attractive feature of the AHS steels is the excellent combination of high strength property and good formability. Dual phase (DP) steel is one of the most important types of the AHS steel. Dual phase steel is one of the family members of high strength low alloy steel which has very good combination of strength and ductility. Due to this unique combination of tensile strength and ductility dual phase steels have a potential commercial importance as engineering materials and this have been considered for application which required good formability for automobile components to reduce the weight of vehicle for fuel economy. These steel have a better deformability than other high strength low alloy steels (HSLA) with similar strength. Mechanical properties of dual phase steels are affected by several factors; some of them are volume fraction and morphology of martensite and ferrite grain size. Dual phase steels show a strong bake hardening effect being of importance for shaping of car body structural parts. The raised yield strength is exploited for improved crash resistance. Especially the automotive industry has a growing interest in using this effect.

In the present investigation, an attempt is made to study the effect of quenched and inter-critical heat treatment on mechanical properties of plain low carbon steel. The idea of selecting this composition was to observe the variation in tensile strength and hardness with variation in carbon contents and to compare the results with those of our earlier study for nearly eutectoid steel. In this area many researchers have worked and their conclusions are depicted as blow before starting the research on proposed area:

A.S.K. Akay, M. Yazici, A. Bayram, A. Avinc studied Fatigue life behaviour of the dual-phase low carbon steel sheets and concludes that

1) Intermediate quenching of low carbon steels yielded a material with a ferrite–martensite (needle like) microstructure. However, it was

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*Corresponding author **Pankaj Sharma** is working as Assistant Professor observed that tempered martensite steels have ferrite–cementite microstructure due to decomposition of martensite in this heat treatment.

2) The samples which were subjected to tensile testing did not exhibit discontinuous-yield phenomena. The highest yield and ultimate tensile strength was achieved in DPM specimens. However, the lowest yield and ultimate strength obtained TM samples. The hardness of DPM steels is higher than TM and as-received steels. This is related to a higher amount of martensite in the steel.
3) DPM samples which have ferrite–martensite microstructure showed fatigue behaviour significantly better than as-received and TM microstructures steels. On the contrary, TM samples showed lower fatigue behaviour than as-received samples. This decreases in the TM samples due to the decomposed martensite to cementite.
4) For DPM structure samples, fatigue crack initiation occurs at the ferrite–martensite interface and especially in ferrite grains. After a number of cycles of repeated stress, the mechanism of crack initiation in DPM structures are proposed to be the dislocation movement at the ferrite–martensite interface and in the ferrite grains.
5) Crack initiation in the TM structure samples occurs along the slip band by intrusion.

B. Lakshmana Rao Bhagavathi, G.P. Chaudhari, S.K. Nath studied Mechanical and corrosion behaviour of plain low carbon dual-phase steels and conclude that: Plain low carbon dual-phase steels with different MVF are obtained by heat treatment using different inter critical soaking times at 740^{0}C. The mechanical and corrosion behaviour of the resulting steels is compared and the conclusions are as follows:

1) With increase in MVF, the UTS of dual-phase steels improved from 428 MPa for DP2 to 575 MPa for DP15 steel whereas, for the same samples the ductility reduced from about 21% to about 13%. The hardness values of all DP steel samples were higher than SA steel and were observed maximum for DP15, i.e. 217 VHN.
2) Fractography of the samples shows the ductile nature of fracture for all steel samples. Though the ductility of DP steel samples was less than SA steel the mode of fracture, upon the transformation from ferrite–pearlite structure to ferrite–martensite structure, remained ductile.
3) The corrosion rates obtained from both potentiodynamic polarization and immersion tests of DP steel samples were marginally less than that for the SA steel samples. This is because the martensite formed in DP steel is structurally and compositionally closer to ferrite matrix phase. Therefore the galvanic couple formed between ferrite–martensite is weaker. This is compared to SA steel wherein pearlite which consists of ferrite and cementite lamellae with 6.67% C in cementite is structurally and compositionally inhomogeneous, which resulted in increased corrosion rates.

C. V. Abouei, H. Saghafian, Sh. Kheirandish studied Effect of microstructure on the oxidative wear behaviour of plain carbon steel" and concludes that

1) The mechanism of wear was mainly oxidative in the range of loads at the sliding speed used in the present study for all the steels investigated.
2) For a given load, the cumulative wear volumes of all the steels increased with sliding distance under dry sliding. However, the wear volume–distance relationship can be represented by two run-in and steady state segments.
3) The steady state wear rate increased linearly with increasing load for all the steels investigated. For a particular load, the wear rate decreased linearly with the increasing hardness.
4) The steady state wear coefficient changed rather sharply between N and DP1 steels; however, there was a less decrease in the wear coefficient between the DP1 and H steels.
5) The average coefficient of friction decreased with increasing normal loads for all the steels, and at a given load the average coefficient of friction decreased with the increasing hardness of the steels.

D. Suleyman Gunduz, Atilla Tosun studied Influence of straining and ageing on the room temperature mechanical properties of dual phase steel" and concludes that:

1) Static strain ageing in micro alloyed dual phase steel was studied by the measurement of the changes in yield stress due to ageing in specimen pre-strained in the range of 2 and 4%. The obtained results from this study as follows:
2) The smooth stress–strain curves in dual phase steel are a result of the motion of free dislocation in the ferrite. These dislocations were produced by the volume change that occurs when the austenite regions transform to martensite.
3) The ageing treatment at 100^{0}C caused an increase in YS. This is due to the formation of solute atom atmospheres around dislocations. Further increase in ageing temperature to 200^{0}C caused a reduction in the yield strength due to over ageing resulted from tempering that starts in martensite.
4) Variation of pre-strain in the range 2 and 4% has negative effect on the changes in DY in subsequent ageing, although the dislocation density would probably be increased by increasing the pre-strain from 2 to 4%. This indicated that a change in DY values is insensitive to dislocation density.

5) Dual phase micro alloyed steel pre-strained in tension by 2 or 4% showed certain amount of cleavage pattern, typical of brittle fracture after ageing at 100^{O}C. However, ductile dimpling was found in the samples after ageing at 200^{O}C due to over ageing resulted of tempering effect of martensite and / or coarsening of the precipitates on dislocation.

2. Experimental Procedure

2.1. Material Procurement

Commercial grade steel AISI 1010 containing C (0.09 wt. %), Mn (0.5 wt. %), P (0.05 wt. %) and S (0.05 wt. %) was used in the present investigation. Steel was purchased from Jain Loha Udoyog, Delhi in the form of plates of dimensions 7' x 14'. Chemically testing was conducted to verify the C % and the presence of an alloying metal, if present in the purchased steel. The material used by us is AISI 1010 which has following composition.

Table 2.1 Composition of AISI 1010 Steel

S. No.	Element	Percentage (by mass)
1.	Carbon	0.09%
2.	Manganese	0.5%
3.	Phosphorus	0.05%
4.	Sulphur	0.05%

Fig. 2.1 AISI 1010 Plate

2.2 Metal Cutting

The procured material AISI 1010 available in the form of plates was cut in to bars of required dimensions using Band saw. The required dimensions were cross-section 1 sq. inch and length 4 inches. Further for conducting heat treatment and Micro structure study samples of dimension 1 sq. inch each were prepared.

Fig.2.2 Steel rods and test specimen

2.3. Test Specimen Preparation

2.3.1 Tensile Specimen PreparationTensile specimens as per the E8 standards were prepared by machining the AISI 1010 steel rods of dimensions , cross section 1 sq. inch and length 3.4 inch to the required dimensions as shown in figure 2.3 and table 2.2.

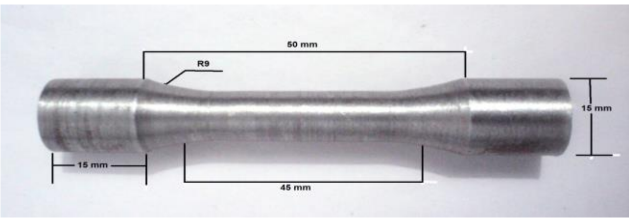


Fig.2.3 Tensile specimens

Table 2.2 Dimension of tensile specimen

S.No.	Dimension	Unit
1.	Gauge Length	45 mm
2.	Diameter	10 mm
3.	Radius of fillet	09 mm
4.	Overall length	80 mm
5.	Length of end section	15 mm
6.	Diameter of end section	15 mm

2.3.2 Hardness Specimen: Hardness is a measure of how resistant solid matter is to various kinds of permanent shape change when a force is applied. Macroscopic hardness is generally characterized by strong intermolecular bonds, but the behavior of solid materials under force is complex; therefore, there are different measurements of hardness: scratch hardness, indentation hardness, and rebound hardness. Hardness is dependent on ductility, elastic stiffness, plasticity, strain, strength, toughness, viscoelasticity, and viscosity. The hardness specimen is of square cross-section of 30 mm and the thickness of 15 mm.

Fig.2.4 Hardness specimen

2.4 Heat Treatment: In order to study the effect of heat treatment on AISI 1010 and for preparation of required steels, heat treatments are performed on the prepared specimen. The heat treatments are done in muffle furnace. The following heat treatments are performed on the steels.

1) Annealing
2) Inter critical Heat Treatment
    - At 750 C
    - At 850 C
3) Oil Quenching

Fig.2.5 Muffle furnace

2.4.1 Annealing: Annealing is a heat treatment wherein a material is altered, causing changes in its properties such as hardness and ductility. It is a process that produces conditions by heating to above the critical temperature, maintaining a suitable temperature, and then cooling. Annealing is used to induce ductility, soften material, relieve internal stresses, refine the structure by making it homogeneous, and improve cold working properties.

We performed the annealing in muffle furnace. The temperature set for annealing process is 950^{0}C. The soaking time for the annealing process is 30 minutes. The cooling is done in the furnace. The cooling time is 24 hours. There are two tensile and one hardness specimen which are annealed.

Table 2.3 Annealing details

Type of Specimen	No. of specimen	Heating Temperature
Tensile	2	950^{0}C
Hardness	1	950^{0}C

Fig.2.6 Annealed specimen

2.4.2 Inter-critical Heat Treatment: The inter-critical heat treatment is used to develop the dual phase consisting of ferrite and martensite phases. The inter-critical heat treatment is done at two temperatures to check the variation in the mechanical properties with the amount of two phases in the dual phase steel. The temperatures are 750 ^{0}C and 850 ^{0}C.

The outline of inter-critical heat treatments is shown in figure 2.7. Point “a” shows the inter-critical at 750 ^{0}C and point “b” shows the inter-critical at 850 ^{0}C. As shown in the figure the point a is close to Ac1 line and should have high percentage of ferrite and the point b is close to Ac3 line and should have high percentage of martensitic phase. The theoretical amount of these two phases at the two temperatures is calculated using lever rule.

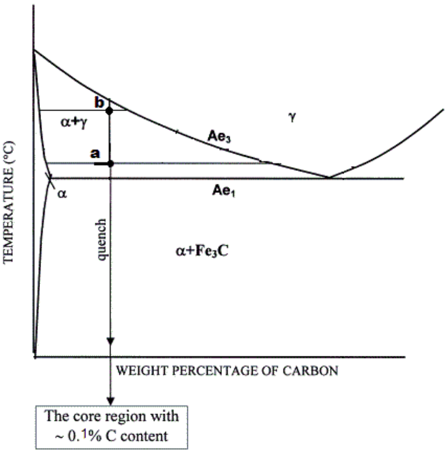


Fig.2.7 Iron carbon phase diagram

1) AT 750 ^{0}C

The samples are heated at 750^{0}C in the muffle furnace. The soaking time is 30 minutes and after that the specimens are quenched in water. The water is at room temperature and stagnant water is used for cooling purpose. There are two tensile and one hardness specimen which are heated at 750^{0}C.

Table 2.4 Inter-critical heat treatment

Type of specimen	**No. of specimen**	**Heating temperature**
Tensile	2	750^{0}C
Hardness	1	750^{0}C

Fig.2.7 Inter-critical specimens at 750 ^{0}C

2) *AT 850 ^{0}C*

The samples are heated at 850 ^{0}C in the muffle furnace. The soaking time is 30 minutes and after that the specimens are quenched in water. The water is at room temperature and stagnant water is used for cooling purpose. There are two tensile and one hardness specimen which are heated at 750 ^{0}C.

Table 2.5 Inter-critical heat treatment

Type of specimen	No. of specimen	Heating temperature
Tensile	2	850 ^{0}C
Hardness	1	850 ^{0}C

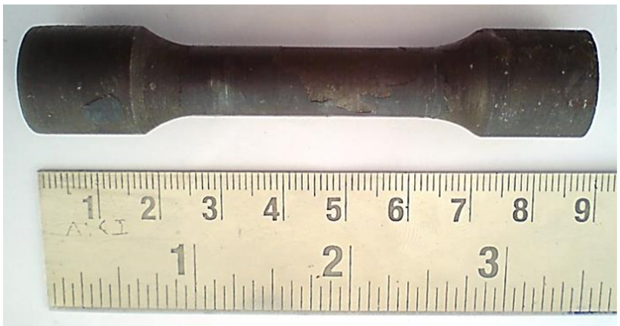


Fig.2.8 Inter-critical specimens at 850 ^{0}C

2.4.3 Oil Quenching: Quenching is the rapid cooling of a work-piece to obtain certain material properties. It prevents low-temperature processes, such as phase transformations, from occurring by only providing a narrow window of time in which the reaction is both thermodynamically favourable and kinetically accessible. For instance, it can reduce crystallinity and thereby increase toughness of both alloys and plastics (produced through polymerization).

The temperature for quenching is 950^{0}C which is above the Ac3 line, at that temperature only austenite is present and on rapid cooling it is converted into martensite phase making the substance harder. The soaking time for quenching is 30 minutes. The quenching medium is servo 4T oil of grade 20W40. The specification of quenching oil is given in the table. The quenching oil is at room temperature during the process. There are two tensile and one hardness specimen which are quenched.

Table 2.6 Specification of quenching oil

SAE	20W-40
Kinematic Viscosity @ 100^{0}C, CST	13.5 – 15.5
Viscosity Index, Min.	110
Flash Point, COC,^{0}C, Min	200
Pour Point, ^{0}C, Max	(-) 21
TBN, mg KOH/gm	5.5 – 8.2

Table 2.7 Oil Quenching

Type of specimen	No. of specimen	Heating temperature
Tensile	2	950 ^{0}C
Hardness	1	950 ^{0}C

Fig.2.9 Oil quenched specimen

2.5 Metallographic Studies

Microstructure is defined as the structure of a prepared surface or thin foil of material as revealed by a microscope above 25× magnification. The microstructure of a material (which can be broadly classified into metallic, polymeric, ceramic and composite) can strongly influence physical properties such as strength, toughness, ductility, hardness, corrosion resistance, high/low temperature behaviour, wear resistance, and so on, which in turn govern the application of these materials in industrial practice

The heat-treated samples were prepared for metallographic studies by grinding them on belt grinder driven by an electric motor. These samples were further polished on emery paper of various sizes followed by cloth polishing using diamond paste of particle size 5 microns. After polishing, the samples were etched with 2% Nital for 10 second and analysed under optical microscope.

Paper Polishing Procedure

Fig.2.10 Steps for paper polishing

Fine polishing is done using diamond paste while is oil soluble of particle size 5 microns was conducted on self-fabricated polishing machine.

Fig.2.11 Polishing Apparatus

Fig. 2.12 Diamond Paste and Spray

2.6 Hardness Test

Hardness is a measure of a material's resistance to localized plastic deformation (e.g., a small dent or a scratch). Early hardness tests were based on natural minerals with a scale constructed solely on the ability of one material to scratch another that was softer. A qualitative and somewhat arbitrary hardness indexing scheme was devised, termed the Mohr scale, which ranged from 1 on the soft end for talc to 10 for diamond. Quantitative hardness techniques have been developed over the years in which a small indenter is forced into the surface of a material to be tested, under controlled conditions of load and rate of application. The depth or size of the resulting Indentation is measured, which in turn is related to a hardness number; the softer the material, the larger and deeper is the indentation, and the lower the hardness index number. Measured hardness are only relative (rather than absolute), and care should be exercised when comparing values determined by different techniques. Hardness tests are performed more frequently than any other mechanical test for several reasons (1) They are simple and inexpensive—ordinarily no special specimen need be prepared, and the testing apparatus is relatively inexpensive (2) The test is non-destructive—the specimen is neither fractured nor excessively deformed; a small indentation is the only deformation. (3) Other mechanical properties often may be estimated from hardness data, such as tensile strength. The bulk hardness of the heat-treated samples was measured at a load of 5 kg and 20 seconds dwell time on calibrated Vickers hardness testing machine using a diamond pyramid indenter.

The harness done is done on four samples each representing the different heat treatment process which is already been performed on these samples. The hardness is measured by Rockwell hardness test. The load is 150 kgf and the indenter is conical.

2.7 Tensile Test

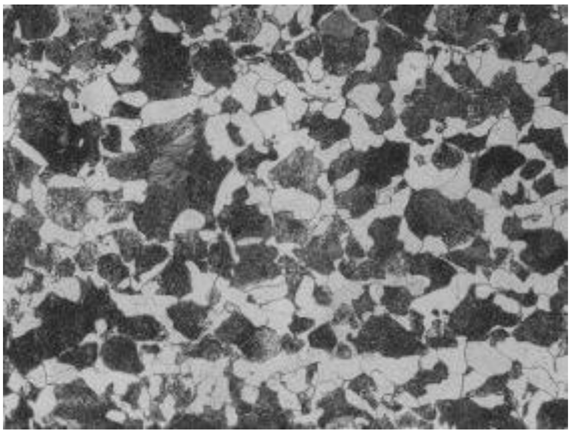
Tensile testing, also known as tension testing, is a fundamental materials science test in which a sample is subjected to uniaxial tension until failure. The results from the test are commonly used to select a material for an application, for quality control, and to predict how a material will react under other types of forces. Properties that are directly measured via a tensile test are ultimate tensile strength, maximum elongation and reduction in area. From these measurements the following properties can also be determined: Young's modulus, Poisson's ratio, yield strength, and strain-hardening characteristics. Tensile test was conducted on UTM with the following specifications under the atmospheric conditions.

Fig.2.13 Tensile Specimens

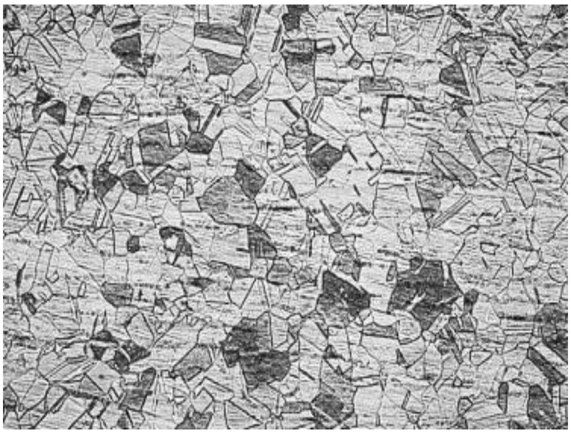
3. Results and Discussion

3.1 Microstructure Analysis

The microstructures are obtained using the optical microscope after polishing the samples. The microstructures are shown in figure 5.1.

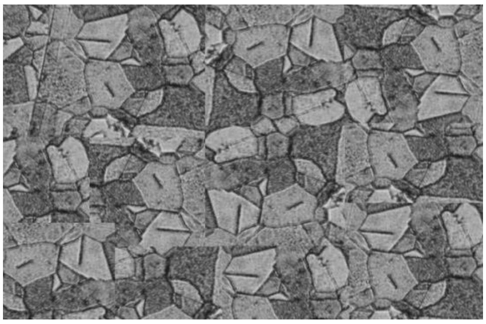


(a) Inter-critical at 750 ^{0}C



(b) Inter-critical at 850 ^{0}C

(c) Oil quenched



(d) Annealed

Fig.3.1 Microstructure of Heat treated Specimen

The picture shown in figure (a) is of inter-critically heat treated specimen at 750 ^{0}C which is a dual phase steel. The black spots show the martensitic phase and the white spots show the ferrite phase. The area covered by black spots is more as expected because this treatment is carried out at a temperature close to Ac3 line at 850 ^{0}C. figure (b) shows the inter-critical at 750 ^{0}C . Here, the area of white spots is more than the black spots which indicates the larger amount of ferrite phase than martensitic phase at 750 ^{0}C. This is also accordance with the theory as this treatment is carried at a temperature close to Ac1 line at 750 ^{0}C. the figure (c), shows the oil quenched specimen, which contains the large amount of martensitic phase. At quenching temperature only austenite is present it is fully converted into the martensite on rapid cooling. The white areas show the lack of complete martensite, it is due to some errors in heat treatment process. The figure (d), shows the annealed specimen the large grain particles is of pearlite which formed due to very slow cooling of austenite in the furnace. All the microstructure results is in accordance with the theoretical results.

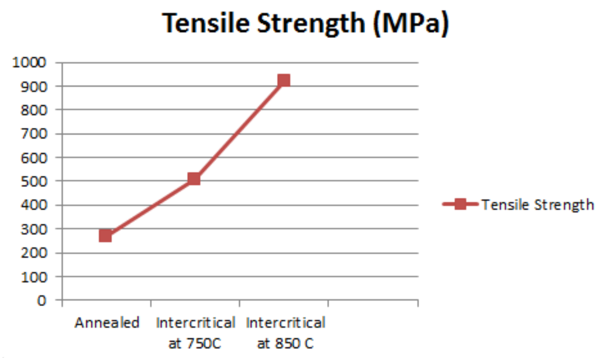
3.2 Tensile Test

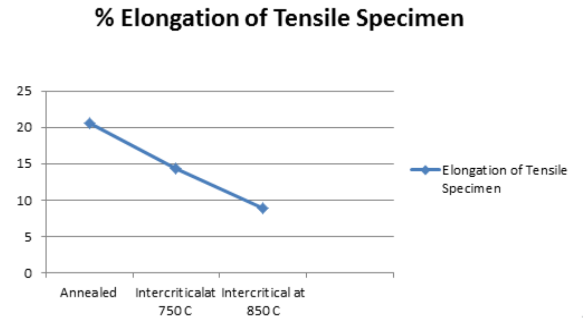
Fig.3.2 Fractured Tensile Specimen

The tensile test is performed on Universal Testing Machine and the following data is collected.

Table 3.1 Tensile Test data

S.No.	Specimen	Tensile strength	Percentage elongation
1.	Annealed	270 MPa	20.6%
2.	Inter-critical at 750 ^{0}C	510MPa	14.3%
3.	Inter-critical at 850 ^{0}C	920MPa	8.9 %





The tensile test is performed on three specimen shown in the table 5.1. The tensile strength of inter-critical heat treatment at 850 ^{0}C is highest followed by inter-critical at 750 ^{0}C and then annealed specimen. This shows that inter-critical has high strength which varies with the percentage of martensitic phase in the dual has region. The percentage elongation is also shown in the table. The ductility in the annealed sample is highest which is due to the weak pearlite phase. The elongation in the inter-critical region is more at 750 ^{0}C then 850 ^{0}C as shown in the table. This is due to the decrease in the ferrite phase as we move from Ac3 toAc1 line. The ferrite is soft and gives ductility to the steel. The desired strength with required ductility can be obtained by varying the amount of phases in the dual phase region.

3.3 Hardness Test

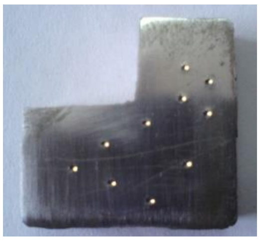
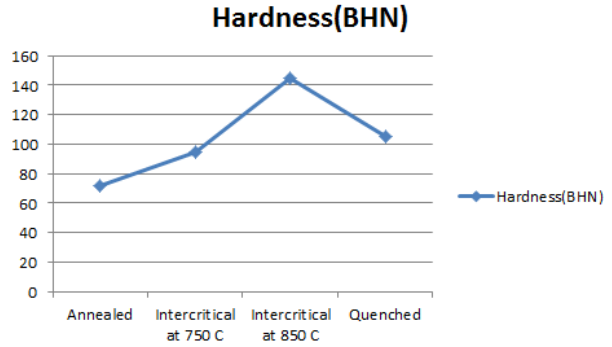


Fig.3.3 Hardness Test Specimen

The hardness is determined by Rockwell hardness test. The hardness values are shown in table 5.2

Table 3.2 Hardness Test Data

S.No.	Specimen	HRB	BHN
1.	Annealed	32	72
2.	Inter-critical at 750 ^{0}C	55	95
3.	Inter-critical at 850 ^{0}C	78	145
4.	Oil Quenched	61	105



Hardness shows the ability of material to restrict the surface deformation against a indenter. The indenter used in Rockwell hardness test is conical in shape. The hardness of annealed sample is found to be lowest which is in accordance with the theory. The hardness of inter-critical sample at 850 C is highest which is due to the high content of martensite. The hardness of inter-critical heat treatment at 750 C is in between the oil quenched specimen and inter-critical at 850. The hardness of inter-critical heat treatment at 750 C is less than at 850 ^{0}C due to the less content of martensite at 750 ^{0}C. The hardness increases with the content of martensite in the dual phase region.

Conclusion

The project work is composed of number of heat treatments on low carbon steel and the mechanical behaviour has been studied. The aim of this study is to develop the dual phase steel and compare it with the annealed and oil quenched properties. Following are the conclusion of this study.

1) Microstructure Study: Martensite is randomly distributed in ferrite phase in dual phase steels. The percentage of martensite increases with the heating temperature in the dual phase region. This is deduced from the theoretical analysis and by mechanical test performed on various heat treated specimen.
2) Tensile Strength: The ultimate tensile strength is increased in the dual phase steel which is due to the presence of martensitic phase in the dual phase steel. The tensile Strength values for annealed, ITC at 750 ^{0}C and ITC at 850 ^{0}C are 270MPa, 510 MPa, 920 MPa respectively. The low tensile strength of annealed is due to the pearlite phase present which is a result of very slow cooling rate. The tensile strength in the dual phase reason is proportional to the amount of martensite in the dual phase steel. As the percentage of martensite increases the strength of dual phase also increases, this takes place as we move from Ac1 line to Ac3 line. This advantage of dual phase steel is very useful in application requiring high strength. The dual phase steel is widely used in the automotive industry due to its high strength.
3) Ductility: The ductility value of annealed, ITC at 750 ^{0}C and ITC at 850 ^{0}C are 20.6%, 14.3%, 8.9%. The ductility of annealed specimen is highest as expected due to the presence of pearlite phase in the annealed specimen. The ductility of inter-critically heated specimen is less than the annealed specimen due to the presence of martensitic phase in the dual phase region. The ductility is goes on reducing with the increase in the content of martensite as we move from Ac1 line to Ac3 line. Hence, a correct combination of strength and ductility can be obtained in the dual phase region with the variation in temperature in the inter-critical region. The feature of dual phase steel to have high strength and sufficient ductility is very important as it required in many application to have ductility with high strength.
4) Hardness Analysis: The hardness value for annealed, ITC at 750 ^{0}C, ITC at 850 ^{0}C and quenched samples are 72, 95, 145, 105 respectively. The inter-critical heat treated steel at 850 ^{0}C is hardest while the annealed specimen has lowest hardness. The oil quenched specimen has less hardness than the inter-critical heating at 850 ^{0}C because the cooling medium in inter-critical heat treatment is water instead of oil which provides more faster cooling than the oil medium used in the quenching process. This makes dual phase steel more useful that the high hardness can be obtained without using high more costly oil for quenching.

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