Mechanical Characterization and Microstructural Analysis of AISI 4340 Ferrite-Martensite Dual Phase Steel

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***Abstract* —Present investigation deals with the mechanical properties and microstructure of dual phase (DP) steel. Normalizing and intercritical annealing heat treatments were carried out at 900, 750, 770, and 790 °C and DP ferrite–martensite steel was obtained. Interaction behavior of both phases has been analyzed through tensile, hardness and impact strength. Comparison of the DP steel with normalized steel has revealed that hardness and tensile strength increases as intercritical temperature increases. Similarly ductility and toughness decreases as the intercritical temperature increases and normalized steel shows better elongation and toughness. The microstructure analysis shows, as the intercritical temperature increases, martensite quantity increases with decrease in ferrite content, which results in improvement in the tensile strength and hardness. The results have shown a decrease in the ductility and toughness as the volume of martensite increases.**

***Index Terms*—dual phase steel, ferrite, martensite, microstructure**

I. Introduction

In the present day, steel plays an important role in industry to modify the properties of the material. Especially, dual phase (DP) structure having more significant effect in automobile industry. These structures have high strength besides good formability and high energy preoccupation in accidental cases. These mechanical properties originated from the different phases in microstructure with considerable amount of elongation and strength.

Heat treatment is a method of heating and cooling in different time intervals and rates to vary the properties of the material [1-2]. During heat treatment of steel, type of phases, weight percentage of phases at lower temperature, grain size of the material may vary depending on time and cooling method. Some of the desired mechanical properties such as hardness, toughness, yield strength, ultimate tensile strength, young's modulus and percentage elongation may be incorporated by tailoring the heat treatment process parameters [3]. The microstructural parameters varied significantly with carbon content and transformation temperature [4]. The microstructural parameters of significance are the volume fraction, size, and distribution of the constituent phases [5]. The most important heat treatment methods like normalizing, annealing, austempering, DP hardening (ferrite-bainite and ferrite-martensite etc.) and conventional hardening are used to alter the properties. Today, among different engineering materials available, steel is the most useful structural material for general applications. Annealing is the heat treatment process wherein a material is softened by coarse grain structure with enhanced creep property [6]. Annealing process involves heating of steel to super critical temperature followed by controlled slow cooling to form coarser or medium pearlitic phase at room temperature. Well distinguished lamellar colonies of ferrite-cementite (pearlite) microstructure are obtained if the process variables are tailored suitably [7-8]. It is used where maximum ductility and appreciable level of tensile strength are required in engineering materials. In normalizing, the material is heated to the austenitic temperature range and critically cooled in air. This treatment is usually carried out to obtain fine pearlitic colony followed by grain refinement, which results in better machinability due to the development of moderate strength and hardness levels [9-10].

In DP structures two varieties are possible like ferrite-martensite (F-M) and ferrite-bainite (F-B). DP structure results in moderate hardness and toughness, so that machinability of the component is improved i.e., DP structure provides balanced bulk properties desired for machining [11-12].

Hardening by water quenching yields excellent hardness with the sacrifice of toughness. This property variation is due to the lattice distortion caused by the formation of supersaturated harder martensitic phase.

Sensitivity of DP steel depends on several parameters including room temperature phase, volume percentage, grain size as well as the shape of the structure. Ravi Kumar et al. [13] concentrated the efforts on the effect of austenite decomposition rate on microstructure and mechanical properties of DP steel. Thin steel sheets which are austenitized at different annealing temperatures are used for the study. These sheets are rapidly quenched

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at intercritical temperature (800˚C) in order to obtain the isothermal decomposition of austenite. The SEM analysis revealed the ferrite nucleation and growth along grain boundaries which formed the ferrite channel around martensite. Results have shown the local martensite lath damage. It has also shown the alternate way of inducing ductility in high strength DP steel. Study done by Bag et al. [5], reported the intercritical annealing treatment for boron and vanadium containing micro alloyed steel to obtain ferrite martensite DP structure. Volume fraction of martensite is varied from 0.3 to 0.8 by controlling partial annealing treatment temperature. The ultimate tensile strength and impact properties of these steels are analyzed and compared with step quenched steels. Finer microstructure has shown good mechanical properties. The structure with 0.55 volume fraction of martensite with ferrite showed good impact and optimum tensile strength. Increased volume fraction of martensite has decreased the impact strength of the material. Yong-Gang Deng et al. [14] investigated the mechanical properties of DP steel and microstructure of the low carbon steels and found that intermediate quenching resulted in larger volume of tough martensite. The analysis of the fractured surface has revealed that ferrite-martensite interfaces are the most susceptible for micro void nucleation. However, martensite micro cracks are also observed in step quenching sample, and the micro voids are nucleated within the ferrite grain in intermediate quenching sample. Ebrahimian et al. [8] investigated the mechanical properties of ferrite-martensite DP steel and effect of volume fraction on different properties. The study has shown that hardening behavior was significantly influenced by ferrite and martensite volume fractions in DP microstructures. Also, the ferrite hardness is continuously decreasing with increasing ferrite volume fraction along with increase in bulk hardness with the increase of martensite volume fraction.

II. Material Properties and Experimental Methods

AISI 4340 steel is a low alloy medium carbon steel, containing different alloying elements such as chromium, nickel and molybdenum. Chromium and molybdenum serve as ferrite stabilizers or carbide formers to improve hardness and wear resistance of the steel with better strength. Chromium also improves corrosion and wear resistance. Nickel is a strong austenite stabilizer which improves strength, toughness, hardenability properties, hot hardness, corrosion and wear resistance. This alloy steel has got high impact resistance and strength when grains are refined. The addition of molybdenum also prevents the steel from being susceptible to temper embrittlement. Thus, the alloying addition not only improves the existing properties but also imparts new properties to the plain carbon steel. Table I shows the spectrometric analysis of AISI 4340 steel with clear depiction of the wt. % of various alloying elements present in the steel.

TABLE I. Primary Alloying Elements Present in Medium Carbon AISI 4340 steel

Type of Steel	Element Wt.%					
	C	Mn	Si	Cr	Mo	Ni
AISI 4340	0.35	0.58	0.25	1.16	0.25	1.24

A. Specimen Preparation

Tensile test:

Specimens are prepared as per ASTM E8M standard (Fig. 1). The turning operation is carried out on CNC turning centre.

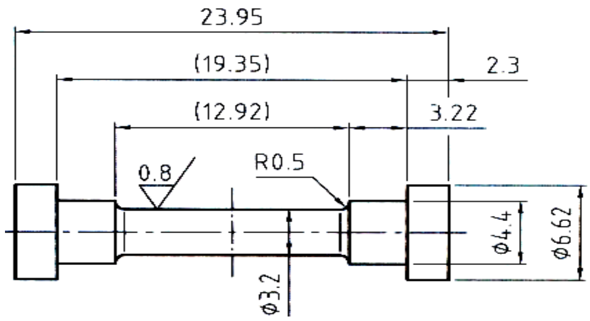

Figure 1. ASTM E8M Tensile test specimen. (All dimensions are in mm)

Impact test (Charpy method):

Specimens are prepared as per ASTM E23-020 standard - Type A (Fig. 2).

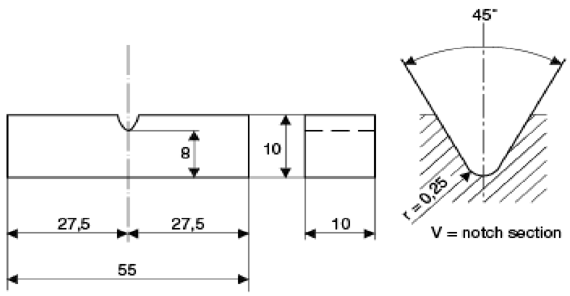

Figure 2. ASTM E23-020 Charpy test specimen. (All dimensions are in mm)

Hardness test:

Rockwell Hardness test is performed as per ASTM E18-02 standard. The bar stocks are cut to 25 mm length using power hacksaw. The turning and facing operations are carried out on center lathe.

B. DP Heat Treatment

In the present investigation, the steel used to produce a DP ferrite-martensite structure is heated to intercritical temperature followed by quenching in water. Before heat treating the steel to produce DP structure, it is heated at 900 ˚C (above the upper critical temperature) isothermally for 2 hours followed by air cooling in atmospheric conditions as shown in Fig. 3. This produces a fine grained room temperature structure.

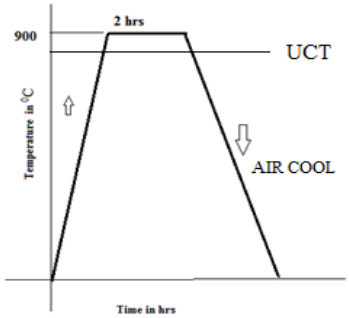

Figure 3. Heat treatment cycle for normalizing.

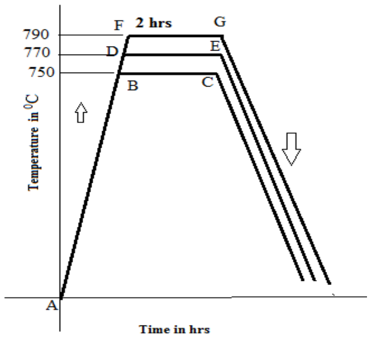

Figure 4. DP heat treatment cycle.

The normalised structure is reheated for 2 hours at three intercritical temperatures (750, 770 and 790 ˚C) to obtain DP microstructures with different martensite and ferrite weight fractions. The normalized specimens are heated to intercritical temperatures for partial phase transformation to austenite followed by water quenching to develop DP structure. Fig. 4 shows the DP heat treatment paths for 3 different intercritical heating temperatures.

After heat treatment the specimens are subjected to tensile, hardness and charpy impact tests and data is recorded. The samples required for metallographic analysis are ground by silicon carbide sheets with the grit sizes of 100, 240, 400, 600, 800, 1000, 1500, and 2000 respectively. Further fine polishing is carried out by disc polishing with the diamond paste. After polishing, the specimens are etched by 2% nital, rinsed with water and dried. The etched specimens are subjected to SEM imaging.

III. Result and Discussion

A. Tensile Test Results

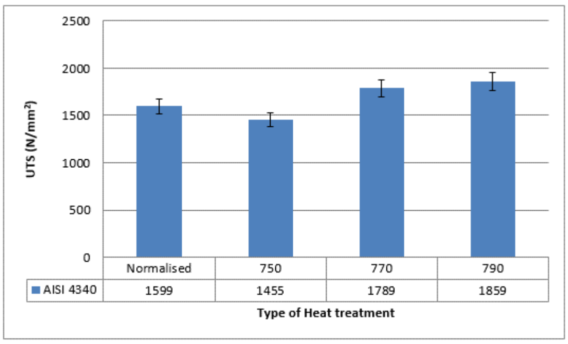

Figure 5. Bar chart showing UTS values for different trials.

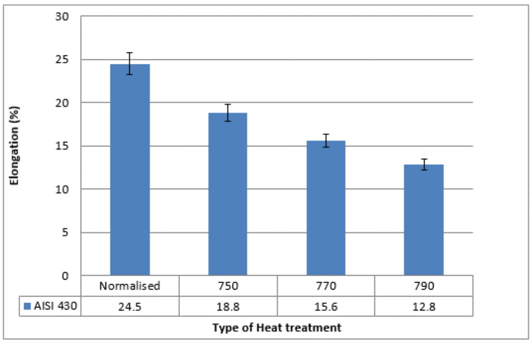

Figure 6. Bar chart showing percentage elongation values for different trials.

DP steel obtained at 750 ˚C austenitising temperature shows slight decrease in UTS compared to normalised steel. Thus may be due to the presence of higher wt. % of ferrite in the specimen with a small amount of martensite in DP steel. As the austenitising temperature increases wt. % of martensite formed also increases [15], which shows further increase in strength value (up to 25% increase) in DP condition obtained at higher austenitising temperature (Fig. 5).

Ductility of DP steel decreases as the austenitising temperature increases. Nearly, 25% decrease in ductility is observed in DP steel obtained at lower austenitising temperature (750 ˚C) compared to normalised steel. This decrease in ductility may be due to the martensite formation mechanism in the specimen even though the wt. % of martensite is less in DP. Normalised specimen shows excellent ductility of 24.5%. As DP autenitising temperature increases the ductility decreases due to the increase in wt. % of martensite in DP. The high temperature austenitized (790 ˚C) DP steel shows almost 50% reduction in ductility (Fig. 6). It is inherent behaviour of martensite phase in low alloy steels.

B. Hardness Test Results

Hardness shows similar trend as that of UTS. Nearly one third increase in hardness is witnessed in DP steel obtained at higher austenitising temperature (Fig. 7).

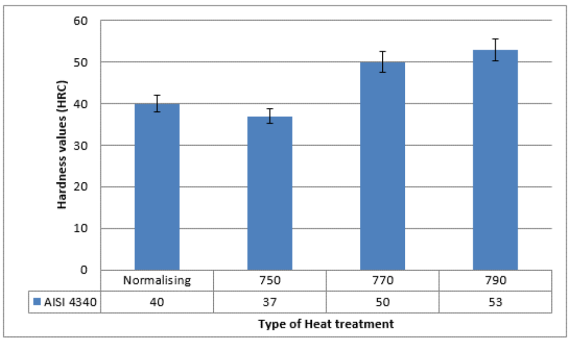

Figure 7. Bar chart showing hardness for different trials.

C. Impact Test Results

Impact resistance of the normalised steel and low temperature austenitized DP steel shows almost same value. As the austenitising temperature increases, the DP steel obtained shows lower value of impact resistance. Accordingly, the DP steel obtained at higher austenitising temperature (790 ˚C) shows approximately 70% reduction in impact resistance as compared to normalized one (Fig. 8). The decrease in impact resistance is due to the increase in wt. % of martensite. Martensite is distorted phase due to its transformation mechanism which develops enormous crystal defects in the lattice to increase the brittleness, hence a decrease in the impact resistance as the intercritical temperature increases [23].

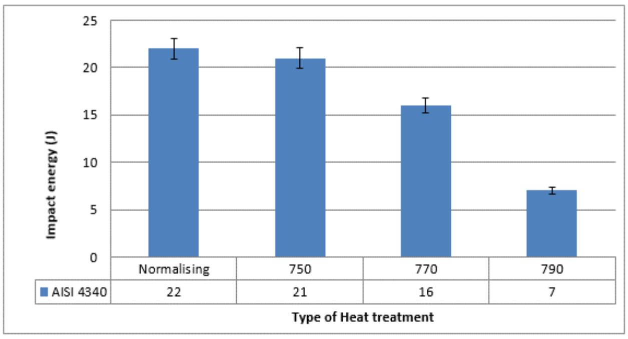

Figure 8. Bar chart showing impact strength values for different trials.

D. Microstructure Analysis

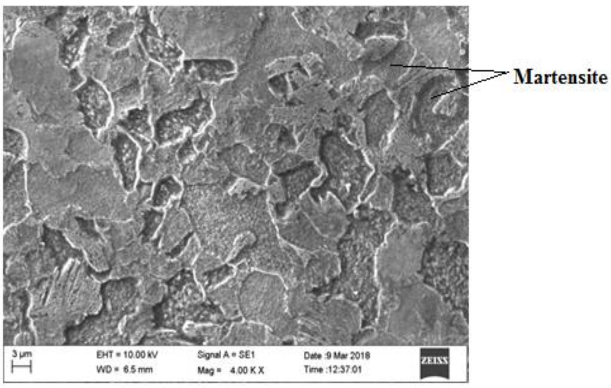

Figure 9. Ferrite-martensite structure of AISI 4340 steel at 750 ˚C

Figures 9, 10 and 11 show the microstructure of DP steel obtained at austenitising temperatures of 750, 770 and 790 ˚C respectively. As the austenitising temperature increases the SEM images of DP structure shows increased amount of martensite phases [16].

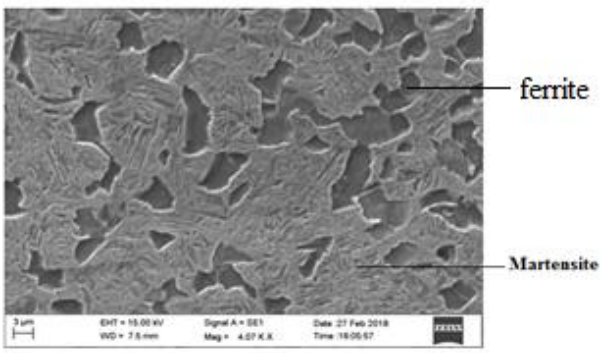

Figure 10. Ferrite-martensite structure of AISI 4340 steel at 770 ˚C.

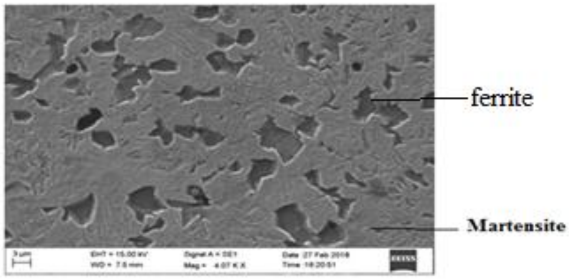

Figure 11. Ferrite-martensite structure of AISI 4340 steel at 790 ˚C.

TABLE II. MICRO HARDNESS (VHN) OF THE SPECIMENS WHICH ARE NORMALIZED AND SUBJECTED TO DP TREATMENT

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Zone 9
Normalised	350	347	349	340	351	353	350	349	348
DP at 750 ˚C	236	580	238	231	587	238	249	230	589
DP at 770 ˚C	218	567	227	566	552	221	220	218	556
DP at790 ˚C	195	520	198	522	527	196	515	194	518

Micro hardness distribution of normalized specimen is more or less same at different zones, which indicates the formation of uniform pearlite phase throughout the specimen. Normalizing always develops fine pearlite phase [17]. In each DP condition, 2 sets of hardness values are observed i.e., lower and higher. It indicates that the DP structure hardness varies at different zones due to ferrite or martensite presence. Ferrite is almost free from carbon, hence shows lower hardness whereas martensite is the harder phase.

As the intercritical temperature (DP temperature) increases, wt. % of austenite formed on heating the room temperature structure increases [18], but solubility of carbon in austenite decreases. Since the parent phase of martensite is austenite and martensite transformation is diffusionless, the solubility of carbon in martensite is same as that austenite and wt. % fraction of martensite is same as that of austenite present. The hardness of martensite is the function of carbon dissolved and directly proportional to the carbon content present in its unit cell. At lower intercritical temperature, wt. fraction of austenite formed is less, but carbon content in austenite is higher (Lever Rule). Accordingly martensite wt. fraction is less but hardness is higher. Hence, in few locations higher hardness is recorded, but value is higher than other DP conditions obtained at higher austenizing temperatures [Table II]. At the higher austenizing temperature (790 ˚C), more locations with higher hardness values are recorded and these values are less than that of lower temperature hardened DP steel. It indicates that parent austenite phase wt. fraction is higher at high temperature and weak in amount of carbon present [17]. This agreement is indirectly supported by the microstructure obtained (Fig. 9, 10 and 11). Similar trend is observed in ferrite hardness values (ranging from 194-249). The hardness of ferrite is also affected by carbon content and as the DP temperature increases, solubility of carbon in ferrite decreases [19]. It causes decrease in hardness value of ferrite. This agreement is well supported by the microstructures shown in figures 9-11.

IV. Conclusion

The AISI 4340 steel is heat treated for dual phase structure with prior normalizing treatment. The treated specimens are tested for mechanical properties along with microstructure. The following conclusions are arrived by critical analysis.

The normalized specimen shows moderate UTS compared to DP steel obtained at higher austenitising temperature (790 ˚C) which shows a maximum value. Lowest UTS is observed in DP AISI 4340 obtained from lower intercritical austenitising temperature (750 ˚C). The DP steel shows increased UTS, ductility and toughness compared to normalized steel. Toughness of the DP steel obtained at higher austenitising temperature (790 ˚C) shows lowest among all. SEM images of DP specimens reveal considerable amount of martensite phases in all 3 steels as the austenitising temperature increases.Micro hardness distribution supports the argument that DP structure is formed by heat treatment and variation in wt. fraction of 2 phase present in DP.

Future Work

Tensile fracture and wear analysis on the dual phase steel at different intercritical temperature may be carried out.

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