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# HEAT TREATMENT AND MECHANICAL CHARACTERISATION OF DUAL PHASE (FERRITE-MARTENSITE) MEDIUM CARBON LOW ALLOY STEELS

Sandesh M Prabhu[1], U Achutha Kini[2], S S Sharma[3], Gurumurthy B M[4]
[1]PG Student, [2,3,4]Faculty
Manipal Institute of Technology, Manipal University, Manipal – 576104, INDIA

***Abstract: Medium carbon steels which find large number of applications derive their properties mainly from the presence of carbon. These properties can be improved by heat treatment or by the addition of small amounts of specific alloying elements. By austenising these steels in the intercritical temperature range and then quenching, dual phase structure (martensitic structure with ferrite) is obtained. In this study, a medium carbon steel SAE 1040 (EN 8) is brought to the dual phase condition at different intercritical temperatures. Its mechanical properties like tensile strength, ductility, hardness and impact strength are ascertained. The same study is extended to two medium carbon low alloy steels SAE 4140 (EN 19) and SAE 4340 (EN 24). Prior to hardening, all these three steels are normalised. A comparison of the behaviour of all the three steels with regard to the mechanical properties is done in normalised condition as well as in dual phase condition to establish the influence of the alloying elements. Tensile strength and hardness were found to increase in SAE 1040 and SAE 4340 steels when austenising and quenching are done at 770 and 790˚C, while ductility and impact strength decreased. In case of SAE 4140, though hardness increased, decrease in tensile strength, ductility and impact strength was observed. SAE 4340 steel was found to give optimum properties in the dual phase condition.***
***Key words: Heat treatment, Dual phase steels, Austenising, Martensite, Ferrite***

## I. INTRODUCTION

Medium carbon steels are widely used for general applications with 0.3 to 0.6 wt% of carbon. Their properties are primarily derived from the presence of carbon. Other elements like manganese, silicon, phosphorus and sulphur may be present in relatively small amounts but their purpose is not principally that of modifying the mechanical properties of steel. An increase in carbon content increases strength and hardness at the expense of ductility. Heat treatment is one of the options for increasing strength so that these steels can be rendered suitable for automotive industrial applications like axles, bolts, crank shafts, connecting rods, torque tubes, etc. Hardening is the most commonly adopted heat treatment technique consisting of heating these steels above the upper critical temperature (to get austenite) followed by quenching so that the austenite transforms into the hard martensite. Alternatively, it is possible to get the martensitic structure along with ferrite. This can be accomplished by heating in the intercritical temperature range (to get austenite and ferrite) followed by quenching [1-3] so that the product has a structure which is a combination of martensite and ferrite. Such dual phase steels exhibit high strength and ductility. They have better mechanical properties as they consist of ferrite and martensite structure [1]. In this study, the mechanical characterisation of one such medium carbon steel namely SAE 1040 (EN 8) which contains about 0.4% of carbon is done by obtaining its dual phase structure at different intercritical temperatures. In spite of these treatments, the medium carbon steels have limitations like low resistance to corrosion and oxidation and also loss of strength at elevated temperatures [4]. The desirable properties of medium carbon steels can be achieved by adding suitable alloying elements [5]. This study is therefore extended to two other medium carbon steels with low alloy content namely SAE 4140 (EN 19) and SAE 4340 (EN 24). SAE 4140 contains molybdenum and chromium in addition to the same amounts of carbon and other elements as present in SAE 1040. SAE 4340 contains nickel in addition to the same amounts of carbon and other elements as present in SAE 4140. A comparative study of the mechanical properties such as tensile strength, ductility, hardness and impact strength for all these three steels hardened at the three intercritical temperatures is carried out to determine the effect of the presence of the different alloying elements on the dual phase properties of these steels.

## II. EXPERIMENTAL DETAILS

### *A. Materials*

Commercially available bar stock of 16 mm diameter was used for all the three steels. The chemical compositions were ascertained through optical spectrometry and are recorded in Table1

TABLE 1: CHEMICAL COMPOSITION OF SAE 1040, SAE 4140 AND SAE 4340 STEELS

| Element in Steel | Wt % | | | | | |
|---|---|---|---|---|---|---|
| | C | Mn | Si | Cr | Mo | Ni |
| SAE 1040 | 0.39 | 0.72 | 0.10 | 0.03 | 0.02 | 0.02 |
| SAE 4140 | 0.39 | 0.65 | 0.21 | 0.93 | 0.23 | 0.02 |
| SAE 4340 | 0.35 | 0.58 | 0.32 | 1.16 | 0.25 | 1.24 |

*B. Specimen preparation*

1) Tensile test: The turning operation is carried out on CNC turning centre. The shape and dimensions of the specimen prepared for tensile test is shown in Fig 1.

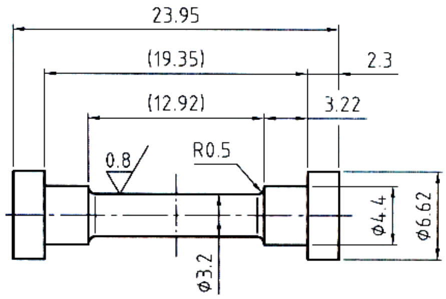
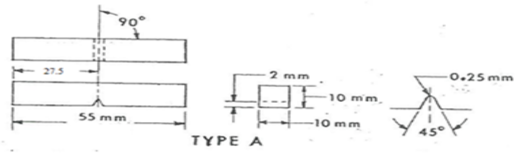



Fig. 1 Tensile test specimen (All dimensions are in mm)

2) Hardness test: Standard specimens are prepared from the bar stocks by turning and facing operations on centre lathe.

3) Impact test (Charpy method): Standard Charpy specimens shown in Fig.2 are prepared using shaping machine with facing and slotting operation.




Permissible variations shall be as follows:

| | |
|---|---|
| Notch length to edge | 90±2° |
| Adjacent sides shall be at | 90°±10 min |
| Cross section dimensions | ±0.075 mm |
| Length of specimen | +0, -2.5 mm |
| Centering of notch | ±1 mm |
| Angle of notch | ±1° |
| Notch depth | ±0.025 mm |
| Finish requirements | 2µm on notched surface and opposite face ; 4µm on the other two faces |

Fig. 2 Charpy test specimen with its dimensional tolerances

*C. Experimentation and Results*

Four sets of specimens (each set consisting of three numbers) for all three materials are prepared for each test. Three trials are conducted for each test and the average value of two consistent readings are recorded. All the specimens are first normalised at 850˚C for two hours. Tensile test, hardness test and impact test are carried out for one set of specimens. The other three sets of specimens are subjected to intercritical austenising for 2 h at 750, 770 and 790˚C respectively and then water quenched at room temperature. The longer heating period ensures the homogeneity of austenite. The above tests are repeated on these three sets of specimens.

*Hardness test:* Hardness test is performed on all the three steels using Rockwell Hardness Tester. The test is carried out on one side of each specimen, at three different places. The hardness is measured as the difference in penetration depths of a diamond indentor under two specified forces namely the preliminary test force and total test force (150 kgf). The readings on C scale are depicted in the bar chart shown in Fig.3.

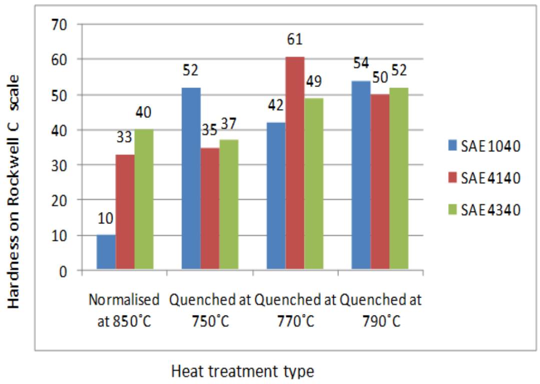



Fig. 3 Hardness values for SAE 1040, SAE 4140 and SAE 4340 steels

*Tensile test:* Tensile test is carried out on electronic tensometer (Kudale instruments Model-PC 2000). The ultimate tensile strength (UTS) and percentage elongation for fracture are obtained and depicted in the bar charts shown in Fig.4 and Fig.5 respectively.

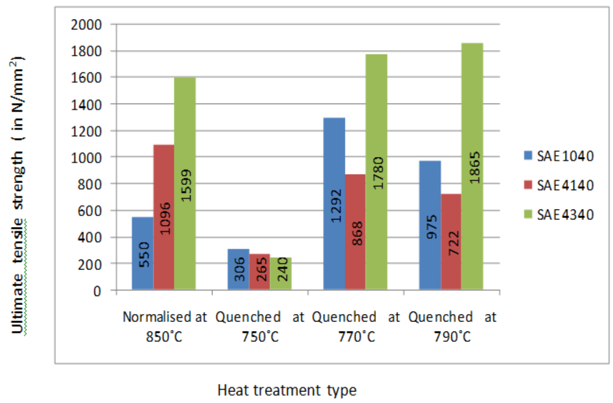



Fig.8: Tensile strength for SAE 1040, SAE 4140 and SAE 4340 steels

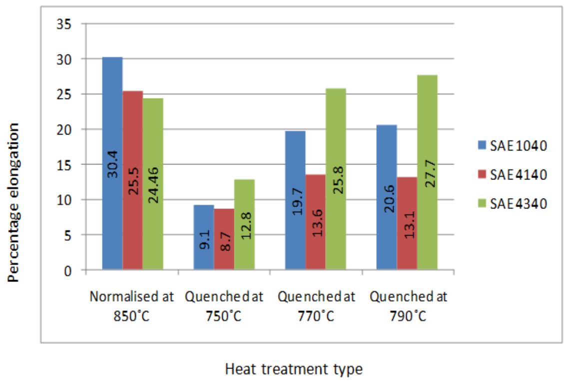



Fig. 5: Percentage elongation for SAE 1040, SAE 4140 and SAE 4340

Impact test (Charpy method): The specimen for impact test is placed on anvil supports to receive the blow of a moving mass that has sufficient energy to break the specimen by impact. Energy absorbed by the broken specimen is measured in joules on a scale. The impact strength values are noted and depicted in the form of bar chart shown in Fig. 6.

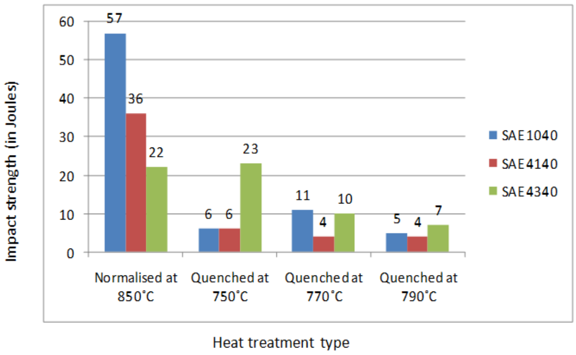



Fig. 6: Impact strength for SAE 1040, SAE 4140 and SAE 4340 steels

## III. DISCUSSION

From the bar charts shown in Fig. 3,4,5 and 6, the observations and analysis are as follows:

*A. Normalising at 850˚C*

Tensile strength and hardness are in the increasing order of SAE 1040, SAE 4140 and SAE 4340. This is due to the presence of chromium and molybdenum as alloying elements in SAE 4140 and SAE 4340 that control grain growth during austenising. This fine grained austenite when cooled in air, transforms into fine pearlite which has high tensile strength and hardness. Moreover, the presence of nickel, further increases the strength and hardenability of SAE 4340. Impact strength is in the decreasing order of SAE 1040, SAE 4140 and SAE 4340. This is due to the formation of chromium and molybdenum carbides in SAE 4140 and SAE 4340 that have low toughness thereby giving less impact strength. In addition these carbides reduce the ductility.

*B. Hardening* - Austenising followed by water quenching When the normalised steel with fine grained pearlite is heated in the intercritical temperature range, transformation to austenite and ferrite takes place. Depending upon the austenising temperature, the amount of austenite and ferrite formed vary and can be determined by applying the lever rule. On water quenching, the austenite plus ferrite structure is converted into ferrite plus martensite structure [3]. Due to the formation of martensite, hardness generally increases especially in plain carbon steels [6]. The hardness values obtained are in line with the ones shown for low alloy steels of 0.38% carbon at different martensite percentages [7].

*Austenising at750˚C:* Here, the solid solution consists of roughly 60 wt % austenite and 40 wt % ferrite. On water quenching, the amount of martensite formed is very less. The small quantity of martensite along with the large amount of proeutectoid ferrite tends to lower the tensile strength and hardness obtained in the previously normalised condition. Moreover annihilation of crystal defects could be taking place. Martensite formation helps retaining the hardness values obtained during normalising in case of SAE 4140 and SAE 4340. However, in case of SAE 1040, carbon, the dominating element combines with the large quantity of ferrite to form insoluble iron carbide thereby increasing the hardness. Hence the hardness increases in the order SAE 4140, SAE 4340 and SAE 1040. The large amount of ferrite present gives the steels very less tensile strength, ductility and impact strength. However, in case of SAE 4340 impact strength slightly increases because of the presence of nickel.

*Austenising at 770˚C:* Holding at this intercritical temperature the solid solution consists of roughly 75 wt % austenite and 25 wt % ferrite (from lever rule). Since austenite forms martensite on quenching, the amount of martensite formed is more than holding at 750˚C and quenching. Yet, there is a drop in hardness value of SAE 1040 from the previous case. This is because the increase in retained austenite favours dissolution of more carbon so that the formation of insoluble iron carbide is retarded. There is substantial increase in hardness of SAE 4340 from the previous value because of alloying of ferrite with chromium, manganese and nickel leading to the formation of acicular ferrite [8]. However, the highest value of hardness in SAE 4140 is due to the formation of insoluble molybdenum carbide and optimum c/a ratio of martensite. Thus the increasing order of hardness is SAE 1040, SAE 4340 and SAE 4140. Impact strength and ductility decrease accordingly in the same order as SAE 1040, SAE 4340 and SAE 4140. Tensile strength and ductility of SAE 1040 increase from the previous values because of the strong strengthening effect of manganese and silicon on ferrite and this reduces impact strength accordingly [9]. The tensile strength in SAE 4140 and SAE 4340 also increases from the previous values as in the case of SAE 1040, for similar reasons. The values of tensile strength are in the order of SAE 4140, SAE 1040 and SAE 4340. The least values of tensile strength and ductility in SAE 4140 are due to the formation of insoluble molybdenum carbide [8]. The highest values of tensile strength and ductility in SAE 4340 are due to the presence of nickel which increases the rate of austenite formation [8].

*Austenising at 790˚C:* Here, the solid solution consists of roughly 95 wt% austenite and 5 wt % ferrite. On water quenching, the amount of martensite formed is very high. Hardness achieved is fairly high and remains almost the same for all the three grades of steels (around 50 HRC). This shows that the hardness developed in this stage of martensite formation is only due to the carbon content in steel [10] and that the alloying elements have no much influence on hardness [8]. Impact strength too is found to be almost the same for all the three materials (around 5~6 J). Its low value is in accordance with the high hardness achieved. Tensile strength and ductility are found to reduce in SAE 1040 and SAE 4140 because the very small quantity of ferrite formed is less susceptible to the influence of manganese and silicon. In SAE 4340, there is further rise in the value of tensile strength and ductility, again due to the increased rate of austenite formation due to nickel.

## IV. CONCLUSIONS

The steels are heat treated and tested in the laboratory conditions. The test results are comparable with the commercially available steels. However, the following conclusions are arrived from the tests.

- The normalised hardness and tensile strength are in the increasing order of SAE 1040, SAE 4140 and
- SAE 4340 while ductility and impact strength vary exactly in the opposite order.
- When austenised at 750˚C and water quenched, tensile strength, ductility and impact strength drastically decreased in all the three steels; hardness decreased in SAE 4140 and SAE 4340 with a stray increase in
- SAE 1040. This shows that martensite formation is not sufficient enough to overcome the effect of large amount of ferrite.
- When austenised at 770˚C and water quenched, tensile strength and ductility increased while impact strength remained low. Hardness showed slight increase in SAE 4340 and a slight decrease in SAE 1040. In case of SAE 4140, there is a drastic increase in hardness with substantial increase in strength and ductility. Alloying elements are found to have lot of influence at this austenising temperature.
- When austenised at 790˚C and water quenched, hardness is found to be around 50 RC in all the three steels. Ductility and tensile strength increased for
- SAE 4340 while a decrease noticed for SAE 4140. Though ductility and hardness increased in SAE 1040, there is a small decrease in tensile strength and impact strength. The least values of impact strength in all the steels along with optimum hardness as well as tensile strength clearly shows the presence of more amount of martensite in all the steels.
- Austenising at 790˚C followed by water quenching is found to give the optimum value of hardness, tensile strength and ductility, with a compromise on impact strength.

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