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LOCHAN SHARMA[1,2*], SANDEEP KUMAR CHAUBEY[1]

TO STUDY THE MICROSTRUCTURAL EVOLUTION OF EN353 STEEL UNDER DIFFERENT HEAT TREATMENT CONDITIONS

Steel is basically used in construction, automobile, buildings, infrastructure, tools, ships, appliances, machines and weapons due to its good mechanical as well as metallurgical properties. Heat treatment of steels significantly enhance its mechanical and metallurgical properties due to the formation of various phases depending upon the type of steel used for specific application. In present study, blank of EN353 grade steel having different sizes were used to investigate the effect of heat treatment and microstructural changes. JMat-Pro software was used to predict the continuous cooling transformation behaviour of EN353 steel. Different phases such as bainite, perlite and other carbide inclusion can be observed in the microstructural examination. Pearlitic microstructure developed for the specimen of size 40×40×40 mm heated at 870°C for 2 hrs and then isothermal heating was performed for same specimen at 600°C for 73 min followed by air cooling.

Relevance Statement: Steel is an important material which is frequently used in almost all areas such as structure building, pressure vessels, transportation and many more other applications. Addition of alloying elements in parent steel significantly improve the metallurgical as well as mechanical properties. Steel properties like tensile strength, toughness, ductility, corrosion resistance, wear resistance, hardness, hot hardness, weldability, fatigue etc. significantly improved with the addition of alloying and heat treatment. Heat treatment processes can be used to improve the properties of steel which are frequently used in many manufacturing industries. Different grades of steels which are heat treated under a set of sequence of heating and cooling to change their physical and mechanical properties so that it can fulfil its function under loading condition. With the help of heat treatment process desired microstructure has been achieved which exhibit good mechanical properties of steels.

Keywords: CCT curves; Cooling rate; Heat treatment; Bainite; Ferrite; Pearlite; Microstructure

1. Introduction

Steel is an alloy of iron and carbon with carbon content up to 2.1%. Steel also contain some other alloying elements which are added to improve its properties to meet the desired end application. Steel properties like tensile strength, toughness, ductility, corrosion resistance, wear resistance, hardness, hot hardness, weldability, fatigue etc. significantly improved with the addition of alloying and heat treatment. Apart from alloying, heat treatment processes can be used to improve the properties of steel. Steel can be classified on the basis of various factors such as amount of carbon content present, like mild steel, medium carbon steel and high carbon steel. On the basis of microstructure in the annealed state hypo-eutectoid, eutectoid, & hyper-eutectoid steel and on the basis of production method used such as forged steel, rolled steel and cold drawn steel [1-3]. It has been observed that engineering materials mostly steels are heat treated under controlled manner under a set sequence of heating and cooling to change their physical and mechanical properties so that it can fulfil its function under loading condition. Heat treatment is a process of producing certain microstructure to achieve desired mechanical properties by combination of timed heating cooling operations. Different mechanical properties which are achieved like Toughness, yield strength, hardness and ultimate tensile strength [4-6]. Some of the previous researcher has performed an experiment on EN353 steel to investigate the effect of cryogenic heat treatment on fatigue strength. Specimen selected for study was 25 mm rod in the hot worked condition. For this he had selected three different type of heat treatment i.e. conventional heat treatment (CHT), shallow cryogenic treatment (SCT) and deep cryogenic treatment (DCT). In this experimentation, 54 samples of size 10cm diameter and 10 cm height i.e. all samples of same size. After different heat treatment, rotating bending fatigue test, micro hardness, retained austenite micro-

1 CHANDIGARH UNIVERSITY, INSTITUTE OF ENGINEERING, MECHANICAL ENGINEERING DEPARTMENT, MOHALI-140413, PUNJAB, INDIA
2 UNIVERSITY CENTRE FOR RESEARCH & DEVELOPMENT, CHANDIGARH UNIVERSITY, MOHALI-140413, PUNJAB, INDIE

* Corresponding author: lochan.e9455@cumail.in

structure and fractography were studied. They had observed that the overall fatigue life improved by 71.42% for SCT over CHT whereas there was a reduction of 26% fatigue life in DCT over CHT [7-11]. In previous study it has been observed the effect of post forging heat treatment on impact fracture toughness and tensile properties. For this micro alloyed cast steel was examined. Samples were heated up to 1230°C and soaked then hot forged. Final temperature after forging maintained above 950°C temperature and then air cooled. Post forging rectangular specimens of sizes of 11×11×60 mm and 11×11×110 mm respectively were cut from the forged piece. Specimens were heat treated at 840, 860, 880, 900, 920 and 950°C for 1 h using an electric furnace followed by air and furnace cooling [12-13]. It was observed that the impact energy of the specimen subjected to air cooling is higher than that cooled in furnace. It is also observed that increment of austenitising temperature induces coarser austenite grains. Useful property of EN353 steel is that its surface hardness is improved by heat treatment and the microstructure is changed from ferrite to martensite [14-16].

2. Experimental procedure

The material was given by Samrat Forging Ltd., Derrabassi EN353 steel was used to study the microstructural behaviour due to heat treatment. The basic property required for gear is its impact strength and wear resistance. EN353 steel was selected for present study because its core is soft so that it can wear sudden jerks during engagement of gear tooth as it produces shock load. And its surface should be hard enough for wear resistance. Soft core is achieved by controlling the microstructure and for wear resistance surface hardening technique was used. EN353 steel is frequently used in many forging industries for heavy work applications like gear manufacturing. EN353 steel material in the form of a blank (75×75×150 mm) was given by Samrat Forging Ltd., Derabassi and its chemical composition is shown in TABLE 1. Seven different specimens of size 60×60×10 mm, 60×60×15 mm, 60×60×20 mm, 60×60×25 mm, 60×60×30 mm, 60×60×35 mm and 60×60×40 mm were cut from the raw EN353 blank with the help of abrasive cutting machine (Fig. 1). Two heat treatments one without isothermal transformation and another with isothermal transformation were used for comparing the results. Heat treatment without isothermal transformation of seven different specimens involves heating at the rate of 600°C/hr up to temperature 870°C then holding the samples for soaking time 2 hour and then normalizing in still air (Fig. 2). Another heat treatment with isothermal transformation for a period of 73 minutes of same seven different specimens was performed at same temperature and time conditions in another furnace. After heat treatment of all the different sized specimens, microstructural

Fig. 1. Specimens of different sizes for heat treatment

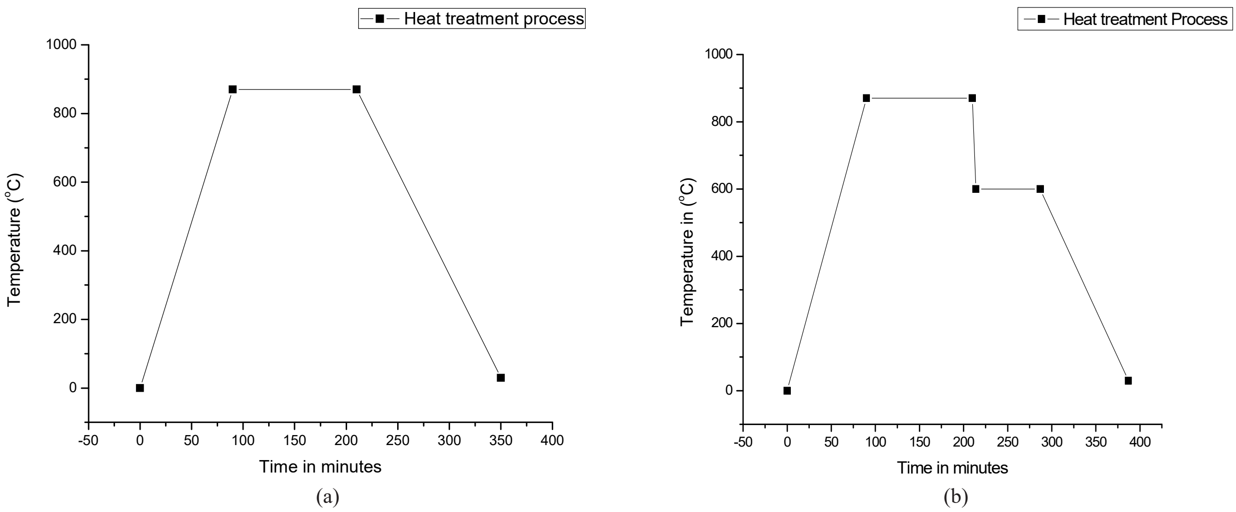


Fig. 2. Line diagrams for heat treatments

TABLE 1

Chemical composition of EN353 steel

Element	C	Mn	Si	S	P	Cr	Ni	Cu	V	Mo	Fe
Weight Percentage	.1694	.6757	.2332	.02127	.01595	.8714	1.142	.0951	.0188	.1089	Rest

behaviour were observed and it was noticed that bigger sized specimens cools faster as compared to small sized specimens.

3. Results & Discussion

The material and problem was given by Samrat Forging Ltd. EN353 steel is basically used to fabricate gears by forging process followed by heat treatment to achieve uniformly distributed fine pearlite microstructure. Actually the problem faced by industry was that bainite patches have been found in microstructure in normalizing heat treatment.It has been observed that fine pearlitic structure has optimum physical properties like toughness, tensile strength, hardness and fatigue strength [17-18]. This is desirable for a material used in gear manufacturing. During tooth cutting operation on gear blank presence of bainite enhances the tool wear. This is because bainite is hard component than pearlite. It is well known fact that tooth profile has very significant role in working of gear and tooth profile is a very critical parameter in gear manufacturing if its tolerance is within some microns level [19].

3.1. Prediction of different phases by using CCT curves

For the prediction of phase after heat treatment CCT curve and cooling rate of sample is required. To obtain CCT curve of EN353 steel JMatPro software was used. The problem associated with this CCT curve is that it tells about start and finish time of different phases at constant cooling rate. In actual heat treatment it has been observed that rate of cooling is varied as a function of time. It also observed that at higher temperature rate of cooling is high and with drop in temperature of the sample the rate of cooling decreases [20-21]. So to predict the exact phase of the sample we have to plot true cooling curve of the sample on the CCT curve obtained from JMatPro software. In present study, to find the cooling rate we have used the basic unsteady state heat transfer equations because cooling of workpiece lies in unsteady state heat transfer condition as its temperature changes with time.

Rate of decrease in internal energy of solid = Heat transfer from solid by convection + heat transfer from solid by radiation is given by Eq. (1)

$$-\rho c V\left(\frac{\delta T}{\delta \tau}\right)=h_c A_c\left(T-T_\infty\right)+\sigma \epsilon A_r\left(T^4-T_\infty^4\right) \tag{1}$$

To convert Eq. (1) in simple form we will consider that amount of heat transfer through radiation is equal to heat transfer through convection. By this method equivalent convective heat transfer coefficient can be calculated. We take convection heat transfer is equal to radiation heat transfer. From Eq. (2) we can find convective heat transfer coefficient for radiation component as mentioned. By putting Eq. (2) in Eq. (1) we will get Eq. (3).

$$h_r A_r\left(T-T_\infty\right)=\sigma \epsilon A_r\left(T^4-T_\infty^4\right) \tag{2}$$

$$h_r=\frac{\sigma \epsilon A_r\left(T^4-T_\infty^4\right)}{A_r\left(T-T_\infty\right)} \tag{3}$$

In Eq. (4) the area for convection A_c and area for radiation A_r are same so we can use the Eq. (5).

$$-\rho c V\left(\frac{\delta T}{\delta \tau}\right)=h_c A_c\left(T-T_\infty\right)+h_r A_r\left(T-T_\infty\right) \tag{4}$$

$$-\rho c V\left(\frac{\delta T}{\delta \tau}\right)=\left(h_c+h_c\right) A\left(T-T_\infty\right) \tag{5}$$

Now in Eq. (5) put overall convective heat transfer coefficient as h_0 given below in Eq. (6) and integrating Eq. (5) we get Eq. (7)

$$h_0=h_r+h_c \tag{6}$$

$$\frac{T-T_\infty}{T_0-T_\infty}=e^{-\left[\frac{h_o A}{\rho c V}\right]\tau} \tag{7}$$

By using above equations we had calculated the cooling rate for each 10°C drop in temperature. We can calculate the time taken by sample for example if the temperature drops from 760 degree to 750 degree, $T = 750$, $T_0 = 760$, $T_\infty = 28$, we can calculate the time τ in sec. Fig. 3 shows the CCT curve of EN353 steel obtained from JMarPro. This figure shows the start and end time of different phases at different temperature. It is also having the line of constant cooling rate.

From this CCT curve (Fig. 3) it is very difficult to predict the different phasespresent in test specimen after heat treatment. The heat treatment used for sample was normalising the test sample by varying the cooling rate. At the start of cooling, the rate is very high and so as the temperature drops the rate of cooling also decreased [22]. From the above mathematical equations the cooling rate was predicted and then the same cooling curve was combined with CCT curve to predict the different phases. Fig. 4 shows the cooling curve of test specimen combined with CCT curve. From Fig. 4 it has been clearly observed that all the samplesof different sizes which was selected for present study have been passing through the region of start of bainite formation and end of bainitic formation in the curve. From the above curve

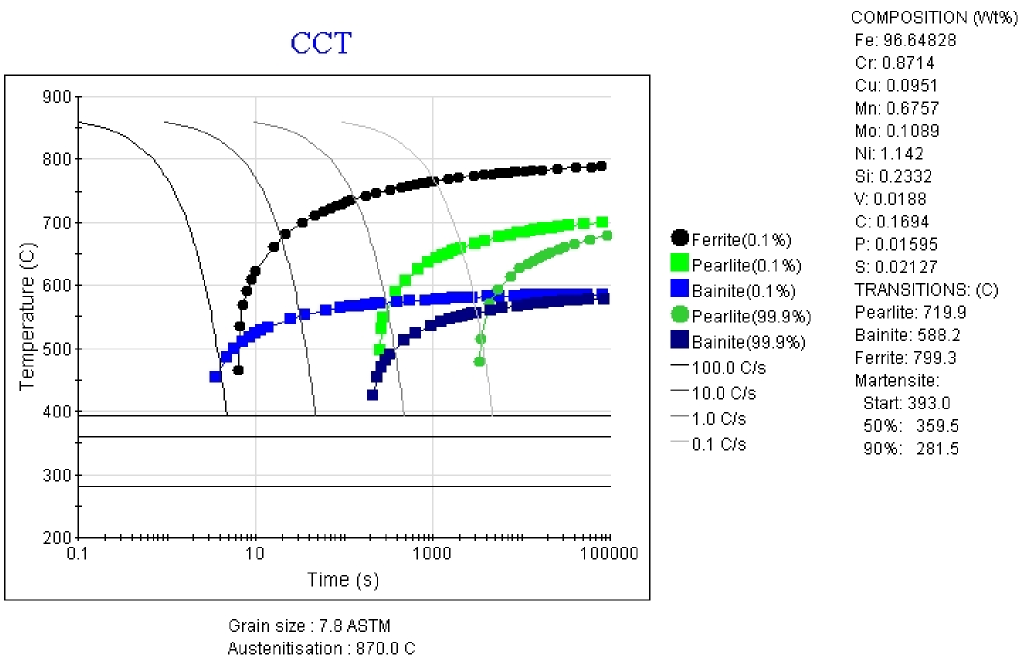


Fig. 3. CCT curve for EN353 steel specimen

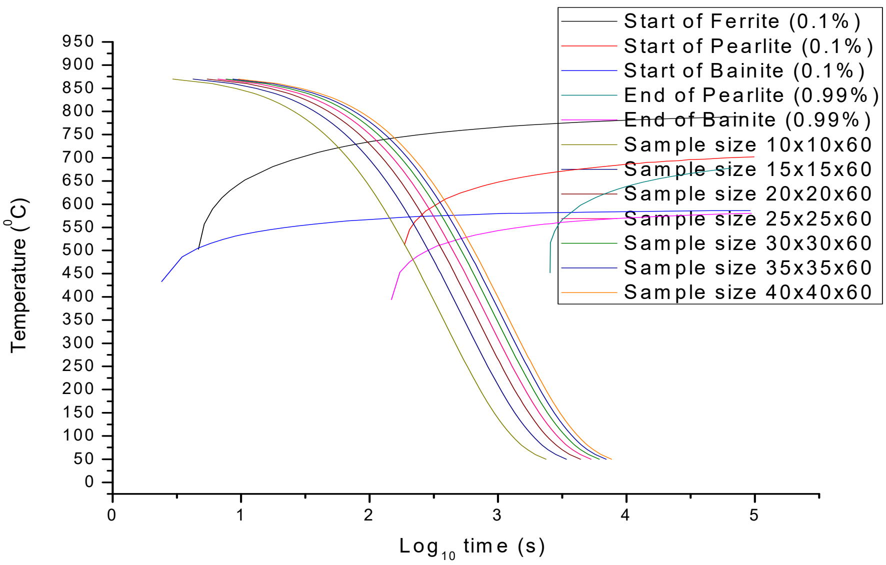


Fig. 4. Cooling curve of test specimen combined with CCT curve

it can be concluded that different sizes of sample will show different phases developedeven if they have been undergone same heat treatment process.

From the above results (Fig. 4) it has been cleared that with normalizing heat treatment it is not possible to get fine peralitic phase. So the isothermal heat treatment has to be combined with normalizing as shown in Fig. 5.

To achieve the required fine pearlitic microstructure different heat treatments of test specimens were performed. For this firstly the sample was heated till austenitic temperature of 870°C soaking of 2 hours than air cooling for 200 sec and isothermal transformation at 600°C for 75 minutes than air cooled. Time and temperature for isothermal heat treatment was taken from CCT curve of EN353 Steel (Fig. 3).

3.2. Microstructural analysis

Microstructural analysis of specimens of different sizes were performed at 100× and 400× magnification (Fig. 6). Different phases such as ferrite, acicular ferrite, bainite, perlite and other carbide inclusion can be observed during microstructural examination. EN353 hot rolled steel generally exhibit polycrystalline microstructure with blend of ferrite and pearlite phases shown in Fig. 6a. Fig. 6(b-h) shows the microstructure with the formation of upper bainite, pro-eutectoid ferrite (allotriomorphic + idiomorphic), acicular ferrite and cementite phases during continuous cooling operation (normalizing in still air) [23-26].

Fig. 6b shows the formation of upper bainite and proeutectoied ferrite for the specimen having size of 10×10×60 at

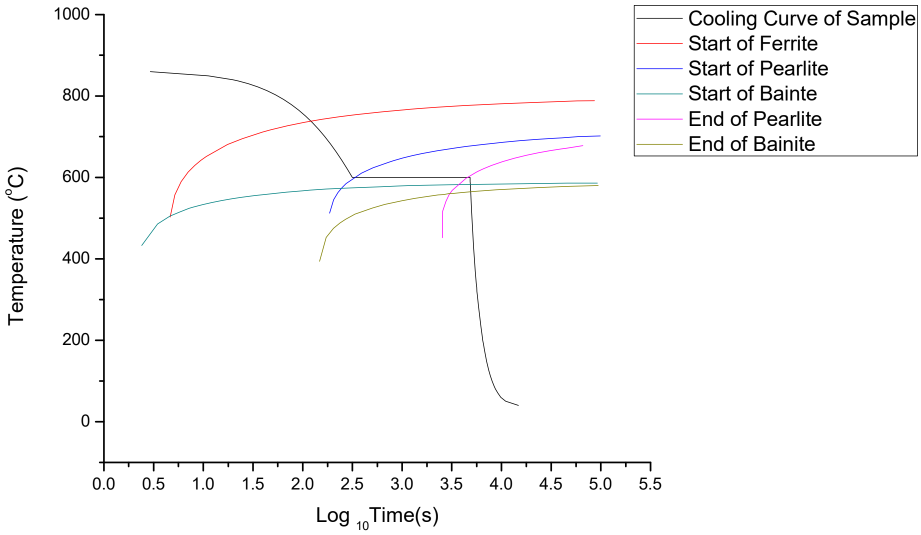
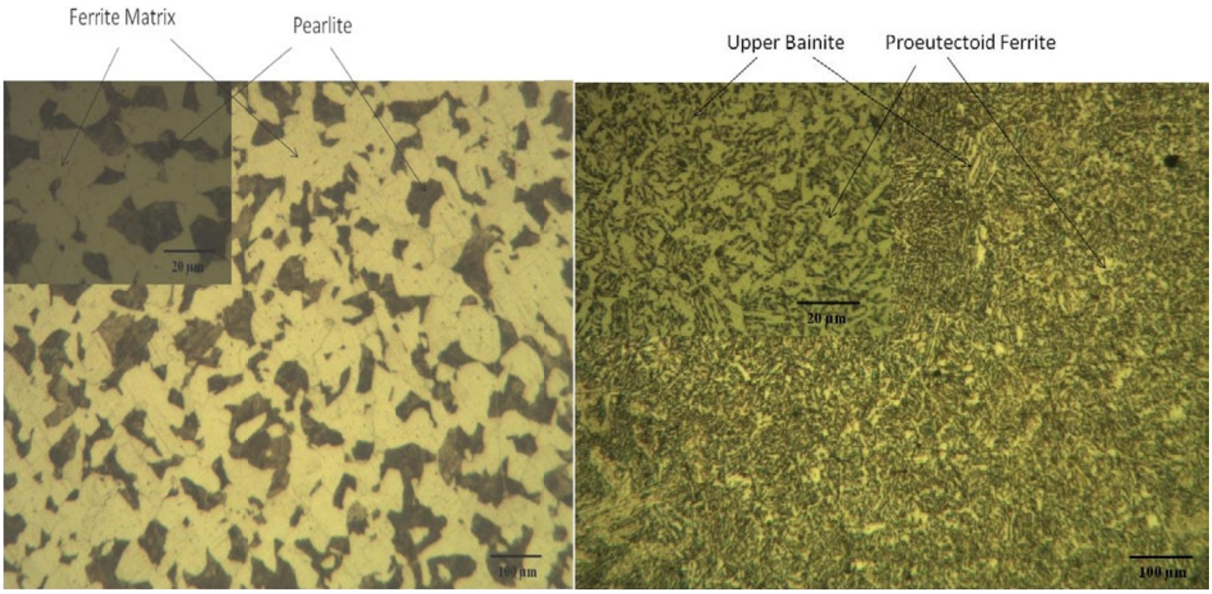
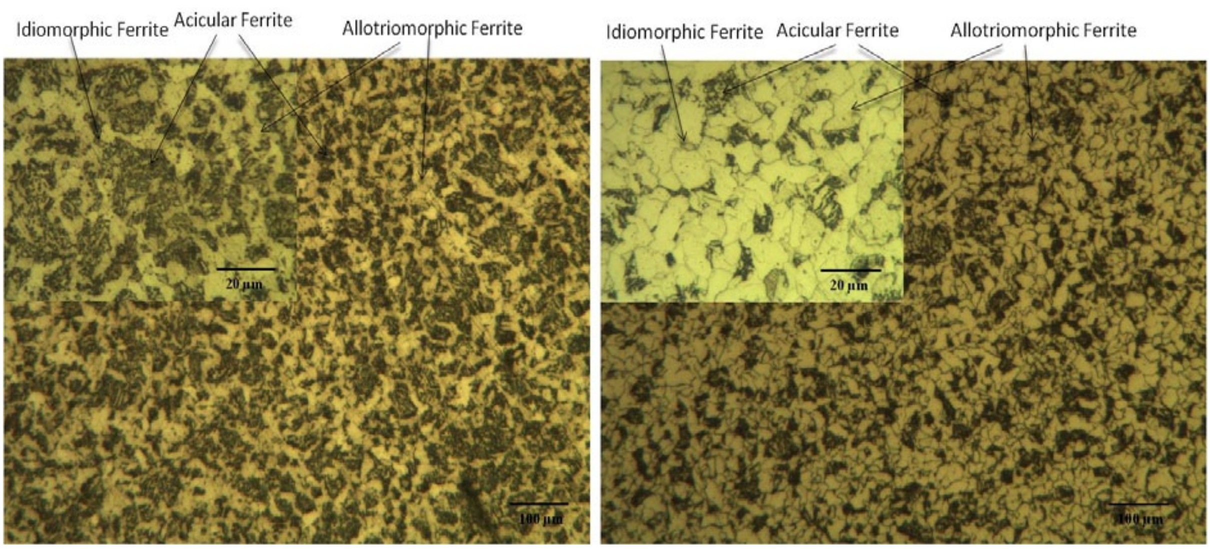


Fig. 5. CCT curve for combined isothermal HT with normalizing HT



(a) Raw EN353 steel

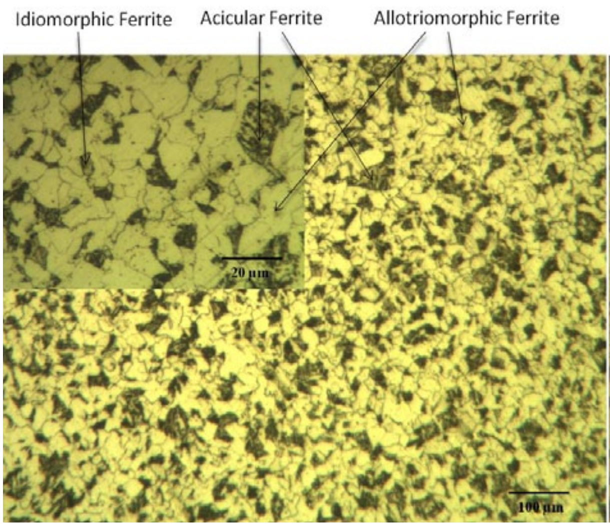
(b) EN353 steel of Size 10×10×60



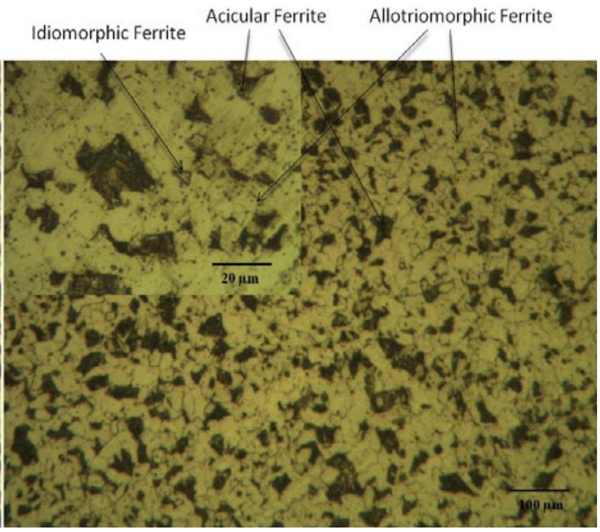
(c) EN353 steel of Size 15×15×60

(d) EN353 steel of Size 20×20×60

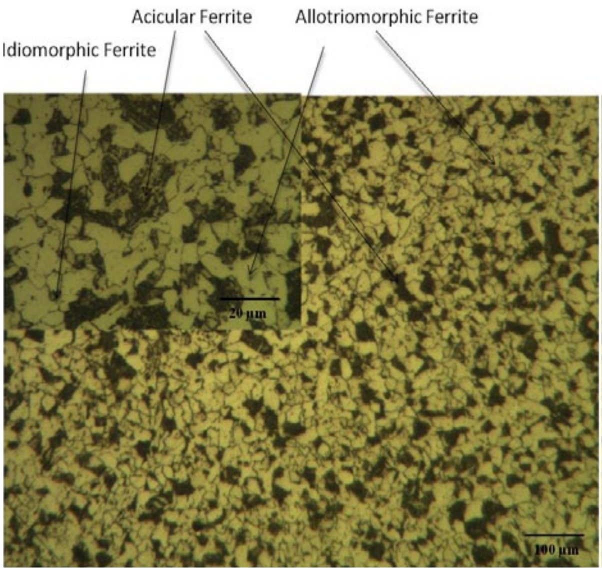
Fig. 6. Microstructural analysis of different sized EN353 specimens at 100× & 400× magnification



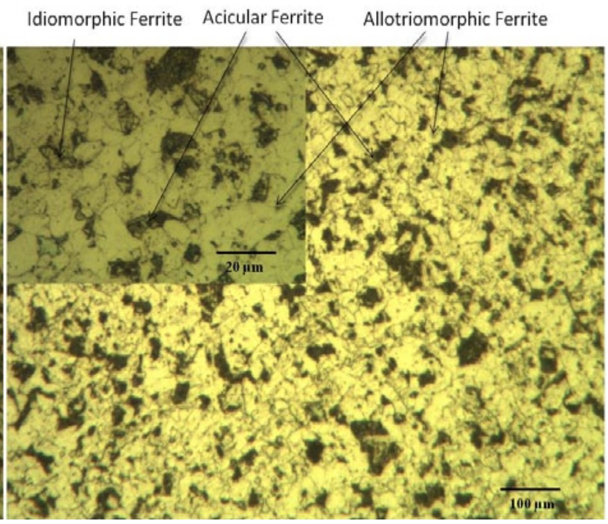
(e) EN353 steel of Size 25×25×60



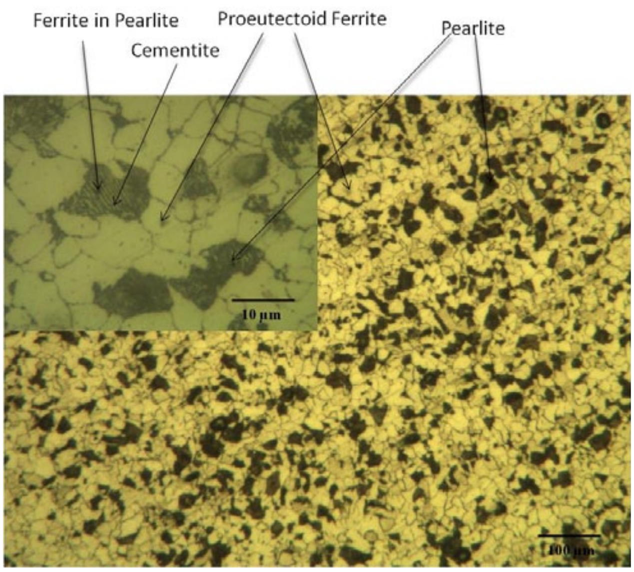
(f) EN353 steel of Size 30×30×60



(g) EN353 steel of Size 35×35×60



(h) EN353 steel of Size 40×40×60



(g) EN353 steel of Size 40×40×40

Fig. 6. Continued

100× and 400× magnification while needle like acicular ferrite microstructure was observed for the specimen of size 20×20×60 at same magnification. In previous literature it has been observed that with both increase in size and cooling rate of the specimen the bainite is getting dispersed in the ferrite and pearlite matrix with some of the cementite formation across the grain boundaries [27-28]. In all the samples (Fig. 6b-h) pro-eutectoid ferrite is formed and present in the form of allotriomorphic and idiomorphic matrix all around the microstructure. Allotriomorphic ferrite is in large quantity with light colour in the microstructure and idiomorphic is in light colour with dark grain boundary of cementite present in small amount in between the allotriomorphic ferrite which is in accordance with the previous literature [29]. It has been observed in the previous study that an allotriomorph has a shape which does not reflect its internal crystalline symmetry. Because it tends to nucleate at the austenite grain boundary surfaces, forming a layer which follow the grain boundary contours. While an idiomorph on the other hand, has a shape which reflects the symmetry of the crystal as embedded in the austenite. Idiomorphs nucleate without contact with the austenite grain surfaces, they tend to nucleate heterogeneously on non–metallic inclusions present in the steel. It forms just below the austenitic temperature during cooling. Below austenitic temperature iron exists in ferritic phase and it is with maximum carbon dissolution of 0.025% where as in austenitic phase it has 2.1% carbon dissolution [30]. In previous study it has been observed that nucleation of acicular ferrite takes place inside the austenite grains as a non-metallic inclusions, whose nature and number can determine the transition from an acicular ferrite microstructure to a bainitic one [31-34]. Acicular ferrite is present as a small light colour grain in between the dark colour pearlitematrix (Fig. 6b-h). The size of acicular ferrite is increasing as the size of sample is increasing.Fig.6g shows the microstructure of specimen of size 40×40×40 mm heated at 870°C and holding it for 2 hrs. at the same temperature followed by air cooling for 2 min. then isothermal heating was performed at 600°C for 73 min followed by air cooling. From Fig. 6g it has been clearly observed the formation of pearlite as a dark one region while proeutectoid ferrite as light one in the matrix. To find the exact percentage content of pearlite and ferrite present in all the microstructures a Dexcel software was used. 20.54% pearlite and remaining pro-eutectoid ferrite was present in EN353 steel of Size 40×40×60 when observed using same software Fig. 7.

4. Conclusions

Raw EN353 hot rolled steel generally exhibit polycrystalline microstructure with blend of ferrite and pearlite phases. Upper bainite patches have been found in the microstructure by heating the EN353 specimen above the austenitic temperature followed by normalizing in air. Different phases such as ferrite, acicular ferrite, bainite, perlite, blend of ferrite & pearlite and other carbide inclusion can be observed in the microstructure for all the differently sized specimens. Number of heat treatment trials performed by the various forging industries has been significantly reduced with the use of CCT curves developed by JMatPro software. Required pearlitic microstructure was developed for the specimen of size 40×40×40 mm heated at 870°C and holding it for 2 hrs at the same temperature followed by air cooling for 2 min then isothermal heating was performed at 600°C for 73 min followed by air cooling.

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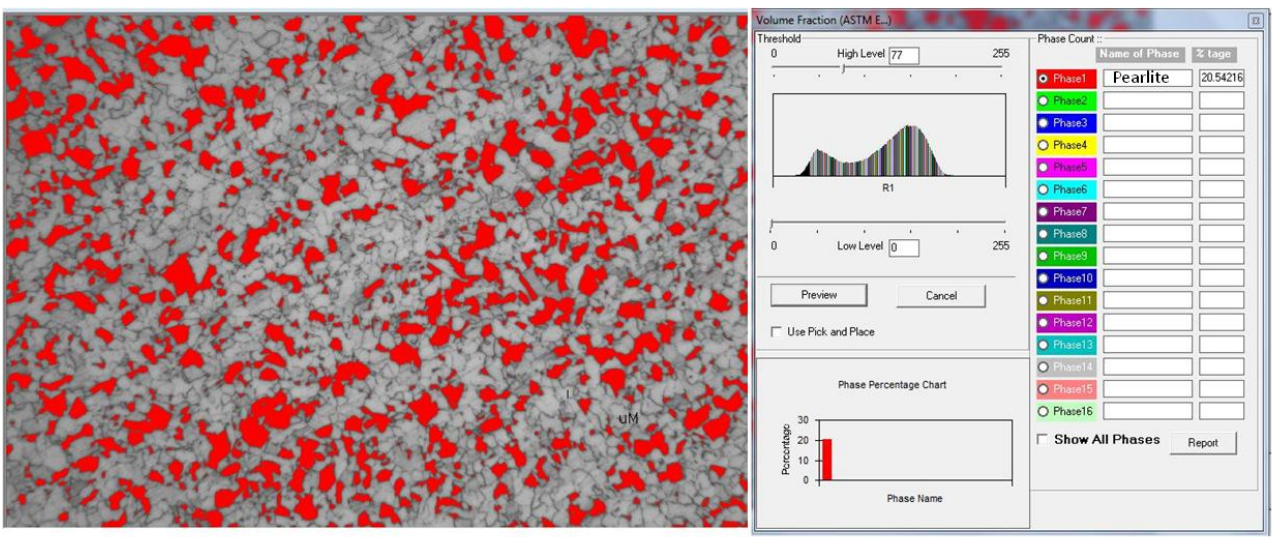

Fig. 7. Prediction of phase percentage in given microstructure

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