

Mathematical Relationship between Ferritic, Pearlitic and Average Grain Size of Steel

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It is an established fact that the grain size of the steel has a marked impact on its mechanical properties. Steel with large grain size has lower yield strength, tensile strength, impact toughness, fatigue life and susceptibility to brittle fracture while has better creep resistance. Besides this it also affects the corrosion resistance and other properties of the steel.

The purpose of this paper is to establish a definite mathematical relationship between the ferritic, pearlitic and average grain size for the steel having ferritic-pearlitic structure. For this reason a hot rolled AISI 1060 sample is selected and are cut into three pieces. Out of these three samples, one sample is normalized from 815 °C and one from 845 °C. Then all the samples are subjected to volume fraction, ferritic, pearlitic and average grain size measurements. Ferritic and pearlitic grain sizes are measured by Intercept Method for Two-Constituents and average grain size is measured by Heyn/Hilliard/Abrams Intercept Method. The results have shown that the experimentally measured average grain size of steel is equal to the sum of the products of ferritic and pearlitic grain sizes with their relative volume fractions that is it satisfies the rule of mixtures.

Keywords: Grain Size, Ferrite, Pearlite, Volume Fraction, Rule of Mixtures

Field of Research: Material and Manufacturing Sciences

1. Introduction

Varying the grain size of the steels plays an important role in improving the mechanical properties of steel (Dieter, 1988). However its measurement has offered a significant difficulty to the researchers and scientists (Voort, 1999). During last century a few remarkable methods are developed which gives significant accuracy and helps to averages the anisotropy.

The objective of this paper is to provide a mathematical relationship between Ferritic, Pearlitic and Average grain size of the steel and also to define the nature of the Average produced by the Abrams three concentric circle intercept method (Single Phase Grain Size Measurement Method) when used over multi-phase structure. In

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most cases at the industrial level average grain size is measured (by using single phase grain size methods) and steel is mostly two-phase structure. So the significance of the proposed relationship is to take into the consideration the type of the average produced (by single phase grain size measurement method). The average grain size of BS 4449:2005 steel and AISI 1060 steel may be equal for certain austenitizing temperature but their properties will still vary (considering only grain size factor) because at the microstructural level the volume fractions the pearlitic and ferritic phases are different for both the steels.

Two steels samples are selected one higher in ferritic volume fraction and other in pearlitic volume fraction. They are subjected to different heat treatments just to homogenize the microstructure. Ferritic, pearlitic and average grain sizes and volume fractions are measured for each sample. Then the measured average grain size (for each sample) is compared with the results which are calculated through the proposed relationship.

2. Literature Review

2.1. Grain Size

2.1.1. Grain

Grain is an area where atoms are arranged in a regular repeated pattern. The orientation of the planes of atoms remains same throughout the grain that is one grain refers to one crystal. The pattern of the arrangement of atom is represented by the unit cell of the crystal.

2.1.2. Grain Diameter

Grain size is related to the average diameter of each grain. The individual grain diameter is of little importance as it is impossible to calculate the diameter of each grain. We only take the average value. The accuracy of the average value depends upon the number of microstructures on which the grain sizes are measured and the sampling procedures.

2.1.3. Grain Boundary

The region formed when the grains in the polycrystalline material meet is called grain boundary. They are the high energy areas and are chemically active in nature (Fontana, 2005).

2.1.4. Definition of ASTM Grain Size Number

According to Vander Voort (1999, pp. 441) ASTM "G" is defined by,

Where.

n= number of grains per square inch at 100x

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G= ASTM Grain Size G number

The above equation can also be written as (Voort, 1999),

As grain size number G increases average grain diameter decreases.

2.2. Importance of Grain Size Measurement

The properties of materials are the function of the constituents appearing in the microstructure, their relative amounts, sizes and morphologies. However grain size that is the average size of the individual grain of a particular phase is an important parameter (Voort, 1999). The mechanical properties like yield strength, tensile strength, toughness, ductility, hardness, fatigue strength, creep strength and susceptibility to brittle fracture are strongly dependent on the grain size of the material.

Besides these, corrosion resistance, ductile to brittle transition temperature, hardenability, electrical and magnetic properties are also affected by grain size.

2.2.1. Effect of Grain Size on Yield Strength

Decreasing grain size increases yield strength of the material (Dieter, 1988). This can be predicted by the well known Hall-Petch relationship,

$$\sigma_y = \sigma_0 + \frac{k}{\sqrt{d}}. \quad \dots \quad (3)$$

Where,

σ_y = yield strength at average grain diameter "d"

σ_0 = Intrinsic yield strength (material's constant)

k = empirical constant

d= average grain diameter

This increase is observed because grain boundaries provide hindrance to the movement of dislocations (Dieter, 1988). However decreasing the grain size to the nano level decreases yield strength (Morris, 2012) because the size of the grains become comparable to the size of dislocations.

2.2.2. Effect of Grain Size on Hardness

Indentation hardness is related to grain size in the same way as equation. 3 (Morris, 2012).

2.2.3. Effect of Grain Size on Toughness

Decreasing the grain size increases the area under the stress strain curve thus increases the toughness of the material (Avner, 1997).

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2.2.4. Effect of Grain Size on Ductility

Ductility is adversely affected by the increase in the grain size. A loss in ductility is observed when grain size is increased. This phenomenon is observed because coarse grain material is brittle in nature (Avner, 1997). There is no direct relationship (known to me) in the literature between grain size and ductility except one found for Magnesium alloys in the paper “Influence of Grain Size on the Ductility of Magnesium Alloys” (Lukáč & Trojanová, 2011).

2.2.5. Effect of Grain Size Creep Strength

One of the major deformation mechanisms at high temperature is grain boundaries sliding. Higher number of grain boundaries will tend to aid this deformation mode. That is why coarse grain size is recommended for higher creep strength (Dieter, 1988). Single crystal turbine blades are the example of this.

2.2.6. Effect of Grain Size on Fatigue Properties

Fatigue strength varies significantly with grain size. Grains of smaller sizes are recommended for good fatigue strength in practice. It is the only parameter on which the Fatigue strength is dependent most (Dieter, 1988).

2.2.7. Effect of Grain Size on Ductile to Brittle Transition Temperature

It is the most important parameter for the constructional materials. Low Ductile to Brittle Transition Temperature (DBTT) is required in this case. It has been observed that increase in ASTM grain size parameter G by 1 (decrease in average grain diameter) decreases the DBTT by 16 °C for mild steels (Dieter, 1988). The equation for the prediction of DBTT with the variation of grain size is similar to that of Hall-Petch equation (Morris, 2012),

Where,

T= DBTT at grain size "d"

T_0 = empirical constant

k = empirical constant

d= average grain diameter

2.2.8. Susceptibility to Brittle Fracture

Higher austenitizing temperature or longer holding time in the austenitic range increases the grain size of steels thus steel becomes susceptible to brittle fracture (Klarić et al., 2009).

2.2.9. Cleavage Fracture Stress

For high strength steels fracture stress is given by (Morris, 2012),

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Where,

σ_f = Fracture stress
 k_f = constant
 d= average grain diameter

That is inversely related to the square root of average grain diameter. However this equation is not valid for the fracture due to transgranular cleavage.

2.2.10. Effect of Austenitic Grain Size on the Hardenability of Steels

Increase in austenitic grain size increases the hardenability of steels (Sharma, Rajan & Sharma, 2011). Hardenability of steels can be defined as the depth to which a material can be quenched when subjected to drastic quenching. Increase in austenitic temperature or holding time in the austenitic range will increase the austenitic grain size by Ostwald Ripening process in which larger diameter grains grow at the expense of grains of smaller size. Increase in austenitic grain size increases the hardenability because it decreases the nucleation sites for the formation of pearlitic phase (Sharma, Rajan & Sharma, 2011). However increase in hardenability due to increase in austenitic grain size is not recommended because due to coarser grain size loss in toughness, ductility and brittleness is observed (Sharma, Rajan & Sharma, 2011).

2.2.11. Effect of Grain Size on Other Properties

Since grain boundaries are the areas of mismatch where the grains of two different orientations meet. They are high energy areas and falls under the category of two dimensional defects (Fontana, 2005). Thus increasing the number of grain boundaries per unit area will make material liable to corrosion. However this is not the major factor affecting the corrosion properties. Etching is a type of selective corrosion in which corrosion is made to occur at grain boundaries which help in revealing the structure at microscopic level of a material (Fontana, 2005). Grain boundaries play a significant role in intergranular corrosion (Smith, Hashemi & Prakash, 2008).

Resistivity also increases with increase in number of grain boundaries or grain boundaries scattering.

2.3. Grain Size Measurement Methods

There are number of methods used for the measurement of grain size. Each have their distinct features and their use for a particular condition can be restricted by the type and nature of microstructure. According to Vander Voort (1999, pp. 437-456) these methods are,

- Comparison with standard charts
 - Fracture grain size

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- Jeffries Plainimetric method
 - Intercept Method (Heyn, Hilliard and Abram)
 - Snyder-Graff Intercept method
 - Grain Size distribution method

According to the scope of this paper only Comparison with standard charts method, Jefferies Plainimetric method and Intercept method (Abram three concentric circles) are discussed here.

2.3.1. Comparison with Standard Charts

In this method the estimation of the grain size is made by comparing the microstructure obtained with the standard charts. The microstructure obtained is compared with the closest micrograph in the standard (Voort, 1999). The grain size of each standard micrograph is given in the standards. For very fine microstructure the magnification is raised and then the contiguous microstructure is found in the standard and correction factor is used to estimate the grain size (Voort, 1999). The correction factor for the magnification is given by,

Where,

M= Magnification used

M_b = Magnification of the chart's microstructure

The grain size is now predicted by using following equation,

$$G = G(\text{Standard chart}) + Q \dots \quad (7)$$

Where,

G= ASTM Grain Size Number

Q= correction factor for the magnification

2.3.2. Jeffries Plainimetric Method

The circle is drawn or placed over the microstructure. Then the numbers of grains which are completely lying within the circle are counted and the grains which are intercepted by the circle are counted separately (American Society for Testing and Materials 2010). Following calculations are performed,

Where,

f= Jeffries multiplying factor

n_1 = number of grains lying completely within the circle

n_2 = grains intercepted by the circle

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Where,

M= magnification

A_c = area of the circle in square millimeters

Average Gain are (A) is given by,

Where,

N_A = number of grains per square millimeters

Average grain diameter (d , mm) is given by,

ASTM Grain size number G is calculated by using,

$$G = 3.22 \log_{10} N_A - 2.954 \dots \quad (12)$$

2.3.3 Intercept Method (Abram Three Concentric Circles)

Intercept method for the measurement of the grain size was first invented by Hyen which was further improved by Hilliard and later on enhanced by Abram (Voort, 1999). Abrams three circle intercept method requires three concentric circles to be placed over a microstructure and counting the total number of grains intercepted by these three circles (American Society for Testing and Materials 2010). The following formula is used,

Where,

$I =$ Mean lineal Intercept

S = Total circumference of the circles

M= Magnification

N= Number of grains intercepted

2.4. Grain Size Measurement Methods for Multi Phase Microstructures

There are methods available for the measurement of the grain size of the individual constituent of the multi-phase microstructures. Most commonly used methods (recommended by ASTM E112) are,

- Intercept method for two constituents

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- Plainimetric method
 - Comparison method

2.4.1. Intercept Method for Two Constituents

Intercept Method for two constituent has gained its popularity because of its ability to produce astonishing results (Voort, 1999). It is similar to the Abrams three circle method with the exception that intercepts of the grains of the phase being considered are only counted and following formula is used,

Where,

I_α = Mean lineal Intercept α phase

N_α = Total Number of intercept of α phase

V_g = Volume fraction of α phase

Conversion of mean lineal intercept can be made by using,

2.4.2. Plainimetric Method

This method is only applicable for the microstructure in which the second phase is in between the matrix grains not inside the matrix grains (American Society for Testing and Materials 2010). This method is similar to the Jeffries Plainimetric method. In this method the area fraction of the phase (whose grain size is to be measured) is found within the circle. In practice the area fraction of the phase whose area appears to be comparatively less is found (American Society for Testing and Materials 2010). The area fraction of the other phase for two phase microstructure is found by difference. Then the grains (of the phase whose grain size is to be measured) lying completely in the microstructure and intercepted by the circle is found separately. The test area is restricted to the area covered by the particular phase within the circle (American Society for Testing and Materials 2010). The following calculations are performed,

Consider two phases α and β are present in the microstructure having are fraction φ_α and φ_β respectively.

So,

Where,

N_α = number grains of α phase per square mm

f_α = multiplying factor

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$n_{\alpha 1}$ = number of α grains lying completely within the circle
 $n_{\alpha 2}$ = number of α grains intercepted by the circle

$$f_\alpha = \frac{M^2}{A_\alpha \phi_\alpha} \dots \quad (19)$$

Where,

M= magnification
A= area of the circle in square millimeters

Then use the equation no. 12 to calculate the ASTM grain size number.

Area and diameter of a phase grain are calculated by using equations 10 and 11 respectively.

2.5. Volume Fraction

Volume fraction of an individual constituent or phase in a multi-phase microstructure is of particular importance as it helps to predict material's properties at the macroscopic level. There are several methods for the determination of volume fraction. According to Vander Voort (1999, pp. 425-432) they are,

- Areal analysis
 - Lineal analysis
 - Point counting method
 - Statistical analysis

Areal analysis and point counting methods are most frequently used for volume fraction determination. However point counting method is important from the scope of this paper.

2.5.1. Point Counting Method

In this method the test grid is placed over the microstructure and the points of the grids lying on the phase of interest are counted and then divided by the total number of points in the grid (American Society for Metals International 2004). Least possible magnification should be used (Voort, 1999). The accuracy of the method depends upon the sampling procedure, number of tests grids used; number of test points in the grid and accuracy of their relative displacement (American Society for Metals International 2004). The following formula is used.

$$V_\alpha = \frac{P_\alpha}{P_T} \dots \quad (20)$$

Where,

V_α = volume fraction of α phase
 P_α = total number of test grid's points lying on α phase
 P_T = total number of test grid's points

3. Experimental Work

3.1. Material Used

3.1.1. B.S 4449:2005 Sample

This sample is taken from thermo mechanically treated bar, taken from Amreli Steels Limited, Karachi. This steel grade is primarily used for reinforcing concrete structures.

3.1.2. AISI 1060

This is a hot rolled sample and it is purchased from market. This grade is suitable for flame hardening, induction hardening and quenching and tempering. In water quenched it can give strength up to 2500 Mpa with 30% elongation and 61 HRC. They are typically used for making hand tools.

3.2. Instrument Used For Microscopy

3.2.1. Metallurgical Microscope

Metkon Inverted Metallurgical Microscope IMM 901 is used to take microstructures. Specifications of this instrument are given below,

- Basic magnifications 100x-1000x.
- Stage; Mechanical stage 200 x 152 mm travel with right hand Coaxial. Dropdown controls, movable range 15 x 15 mm.
- Focusing; Coaxial low position coarse & fine focus controls graduated to 2 microns per division
- Illumination; 6V 20W adjustable light sources with halogen lamp.
- Camera; Canon.

3.3 Heat Treatment Furnace

For heat treatment PROTHERM PLF 120/10 is used. Specifications of this furnace are,

- Maximum operating temperature is 1200 °C.
- Furnace operating atmosphere is air.
- Volume is of 30 liters.
- The furnace has programmable PID controller with single ramp.
- It also posses dual display system for set and actual temperature.
- Heating elements are of Kanthal.

3.4. Setup for the Experiment

For the purpose of the experiment B.S 4449:2005 TMT bar and hot rolled AISI 1060 samples are taken. Three specimens of similar sizes were cut from each hot rolled sample. Two out of three B.S 4449:2005 specimens are given full anneal, one at 875 °C and other at 890 °C. The third specimen is normalized at 890 °C.

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Two out of three AISI 1060 samples are normalized, one at 815 °C and the other at 845 °C. All the specimens are then subjected to volume fraction and grain size measurements.

Fig 1: Heat Treatment Cycles of B.S 4449:2005 Samples

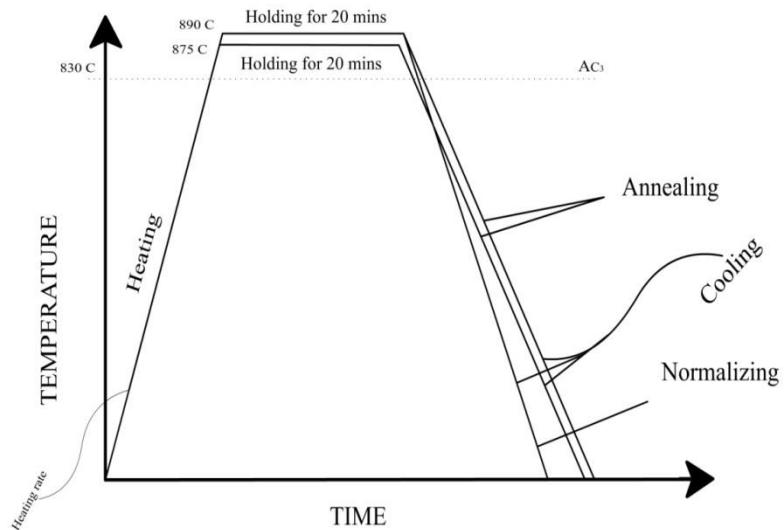
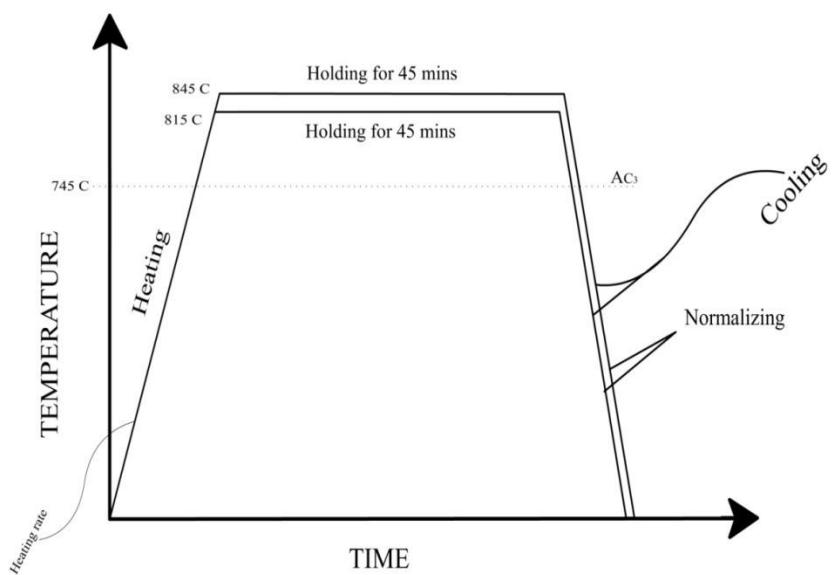


Fig 2: Heat Treatment Cycles of AISI 1060 Samples



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3. 4. 1. Volume Fraction

Volume fractions of all the tests specimens are measured through point count method.

Table 1: Volume Fractions of the Test Specimens

Test specimens	Volume fraction of Ferrite	Volume fraction of Pearlite
B.S 4449:2005 Annealed at 875	0.743	0.257
B.S 4449:2005 Annealed at 890	0.778	0.222
B.S 4449:2005 Normalized at 875	0.605	0.395
AISI 1060 Normalized at 815	0.310	0.690
AISI 1060 Normalized at 845	0.280	0.720
AISI 1060 Hot Rolled	0.280	0.720

3. 4. 2. Average Grain Size Measurement

The average grain size of the test specimens are measured by Abrams Three Circle Intercept Method. The grain sizes of the tests specimen are given in Table 2.

Table 2: Average Grain Sizes of the Test Specimens

Test specimens	Mean lineal intercept, μm	ASTM Grain Size, G
B.S 4449:2005 Annealed at 875	26.60	7.18
B.S 4449:2005 Annealed at 890	26.88	7.15
B.S 4449:2005 Normalized at 875	15.62	8.71
AISI 1060 Normalized at 815	17.40	8.50
AISI 1060 Normalized at 845	21.40	7.80
AISI 1060 Hot Rolled	25.60	7.30

3. 4. 3. Grain Sizes of Ferritic Phases

The average grain sizes of ferritic phase are measured through Intercept Method for Two Constituent. The ferritic grain sizes of all test specimens are shown in the Table 3.

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Table 3: Grain Sizes of Ferritic Phase of the Test Specimens

Test specimens	Mean lineal intercept of Ferrite, μm	ASTM Grain Size, G
B.S 4449:2005 Annealed at 875	29.48	6.88
B.S 4449:2005 Annealed at 890	34.73	6.41
B.S 4449:2005 Normalized at 875	16.44	8.56
AISI 1060 Normalized at 815	9.000	10.3
AISI 1060 Normalized at 845	11.60	9.60
AISI 1060 Hot Rolled	14.40	9.00

3. 4. 4. Grain Sizes of Pearlitic Phases

The average grain sizes of pearlitic phase are measured through Intercept Method for Two Constituent. The pearlitic grain sizes of all test specimens are shown in the Table 4.

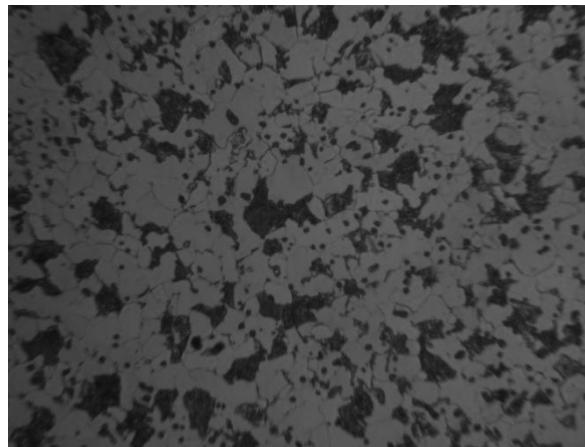
Table 4: Grain Sizes of Pearlitic Phase of the Test Specimens

Test specimens	Mean lineal intercept of Pearlite, μm	ASTM Grain Size, G
B.S 4449:2005 Annealed at 875	20.08	7.98
B.S 4449:2005 Annealed at 890	15.00	8.83
B.S 4449:2005 Normalized at 875	14.52	8.92
AISI 1060 Normalized at 815	21.95	7.76
AISI 1060 Normalized at 845	28.57	7.00
AISI 1060 Hot Rolled	39.10	6.10

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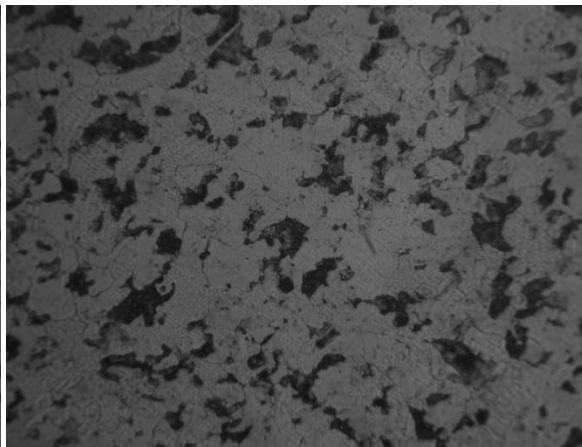
**Fig 3: Annealed (875 °C) B.S 4449:2005
4449:2005**

sample microstructure. Original magnification: 400x



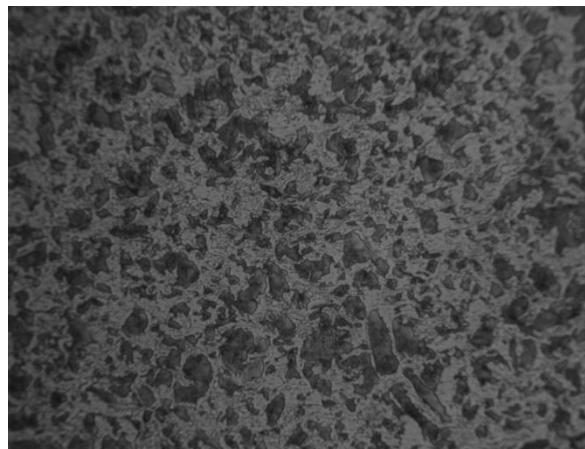
**Fig 4: Annealed (890 °C) B.S
4449:2005**

sample microstructure. Original magnification: 400x



**Fig 5: Normalized (890 °C) B.S 4449:2005
1060**

sample microstructure. Original magnification: 400x



**Fig 6: Normalized (815 °C) AISI
1060**

sample microstructure. Original magnification: 400x

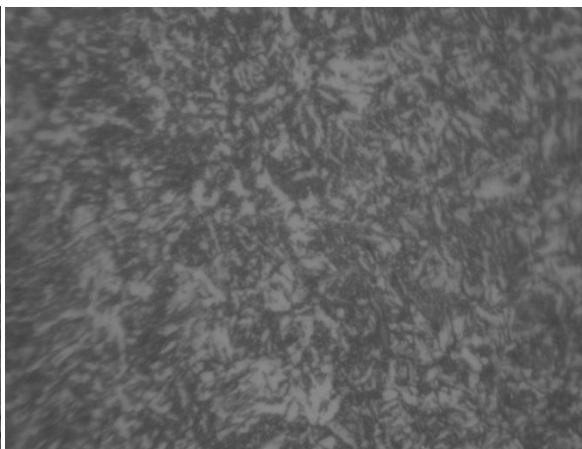
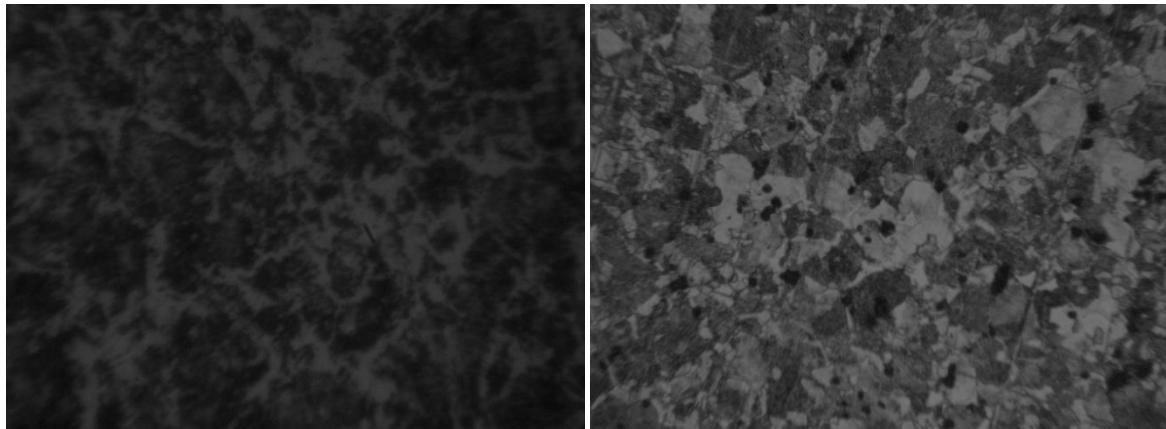


Fig 7: Normalized (845 °C) AISI 1060 sample microstructure. Original sa magnification: 400x

Fig 8: Hot Rolled AISI 1060
microstructure. Original magnification
400x



4. Results and Findings

4.1. Relationship between Ferritic, Pearlitic and Average Grain Size of Steel

After performing a number of measurements it is found that average grain size of steel is approximately equal to the sum of the product of ferritic and pearlitic grain sizes with their relative volume fractions. This relationship is given by,

Or,

Where,

G_{avg} = Average grain size measured by Abrams three circle method

G_f = Grain size of ferrite

G_p = Grain size of pearlite

V_f = Volume fraction of Ferrite

V_p = Volume fraction of Pearlite

In terms of mean lineal intercept,

Or,

$$l = l_f V_f + l_p (1 - V_f) \dots \quad (24)$$

Where,

|= Mean lineal intercept

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I_f = Mean lineal intercept of ferritic phase
 I_p = Mean lineal intercept of pearlitic phase

The calculated average grain size using equation number 1 is shown in the Table 6.

Table 6: Calculated and Measured Grain Sizes

Test specimens	Calculated Average Grain Size, G	Measured Average Grain Size, G
B.S 4449:2005 Annealed at 875	7.16	7.18
B.S 4449:2005 Annealed at 890	6.94	7.15
B.S 4449:2005 Normalized at 875	8.72	8.71
AISI 1060 Normalized at 815	8.55	8.50
AISI 1060 Normalized at 845	7.80	7.80
AISI 1060 Hot Rolled	6.91	7.30

4.2. Relationship between Ferritic, Pearlitic and Average Grain Area of Steel

Since there is no relationship exist between Mean Lineal Intercept "I" and ASTM Grain Size G, ASTM E 112 approximates mean lineal intercepts as average grain diameter which means for the average area of grain mean, lineal intercept is given by,

Where,

A_{avg} = Average Grain Area of Circular Grain

In this respect, using equation number 7 and 9, it can be stated that,

Or,

Where,

A_f = Area of the ferritic grain

A_p = Area of the pearlitic grain

5. Conclusion

Grain size manipulation of different phases for the enhancement of the mechanical properties of steels is the next era in the steel metallurgy. The phenomenon of Dynamic Hall-Petch effect in Twinning Induced Plasticity (TWIP) steels, nano sized k-carbides in Triplex steel; MMFX-Tri-phase nano composite steels are the examples of the steels that derive their exclusive properties through the unique sizes of their phases. Grain refinement is the only strengthening mechanism available that doesn't compromise on the ductility of steels considerably while the other strengthening mechanisms like quenching, cold working, precipitation hardening and alloying decreases the ductility significantly. However accurate grain size measurement on bulk level is an issue.

This paper is an effort to show how the average (similar to the one obtained from method used for single phase structure when used over multi-phase structure) can be obtained by correlating the volume fractions and the grain sizes of individual phases and the dependence of the grain size of individual constituent or phase on volume fraction of steel, because after performing a number of experiments it is found that the grain size of particular constituent in the multi-phase microstructure is directly proportional to its volume fraction. This paper will enable us to find the new methods for the measurement of grain size or in certain cases can enable us to predict the final grain size and related properties before subjecting steel to a particular heat treatment process.

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