Proceedings of the Global Engineering, Science and Technology Conference 2012
28-29 December 2012, Dhaka, Bangladesh

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.

Key words: 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. During last century a few remarkable methods are developed which gives significant accuracy and helps to averages the anisotropy. Abrams Three Circle Intercept Method is one of them. It is one of the fastest and accurate methods which can also be used efficiently for the microstructure having non-equiaxed grains with considerable efficiency (Vander Voort, 1984). A variant of this method called Intercept Method for Two Constituent is extensively used for the measurement of the grain size of a particular phase in a multi-phase structure (ASTM E112, 2010).

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The objective of this paper is to provide a mathematical relationship between Ferritic, Peralitic and Average grain size of the steel and also to define the nature of the Average produced by the Abrams Three Circle Intercept Method (Single Phase Grain Size Measurement Method) when used over multi-phase structure.

2. Literature Review

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 (Vander Voort, 1984). Abrams three circle intercept method require three concentric circles to be placed over a microstructure and counting the total number of grains intercepted by these three circles. The following formula is used,

$$l = \frac{L}{N} \quad (1)$$

$$L = \frac{S}{M} \quad (2)$$

Where,

l = Mean lineal Intercept
S = Total circumference of the circles
M= Magnification
N= Number of grains intercepted

Intercept Method for two constituent has gained its popularity because of its ability to produce astonishing results (Vander Voort, 1984). It is similar to the Abrams three circle method with the exception that intercepts of the phase being considered are only counted and following formula is used,

$$l_\alpha = \frac{V_\alpha L}{N_\alpha} \quad (3)$$

Where,

l_α = Mean lineal Intercept α phase
N_α = Total Number of intercept of α phase
V_α = Volume fraction of α phase

Conversion of mean lineal intercept can be made by using (ASTM E112, 2010),

$$G = -6.644 log_{10}(l) - 3.288 \quad (4)$$

3. Experimental Work

3.1. Material

3.1.1. B.S 4449:2005 Sample

This sample is Thermo mechanically treated Bar, taken from Amreli Steels Limited, Karachi.

3.1.2. AISI 1060

This is a Hot Rolled sample and it is purchased from market.

3.2. Microscopy

3.2.1. Metallurgical Microscope Model

Metkon Metallurgical Microscope IMM 901 is used for microstructures.

3.3 Heat treatment Furnace

For heat treatment PROTHERM PLF 120/10 is used.

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.

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.

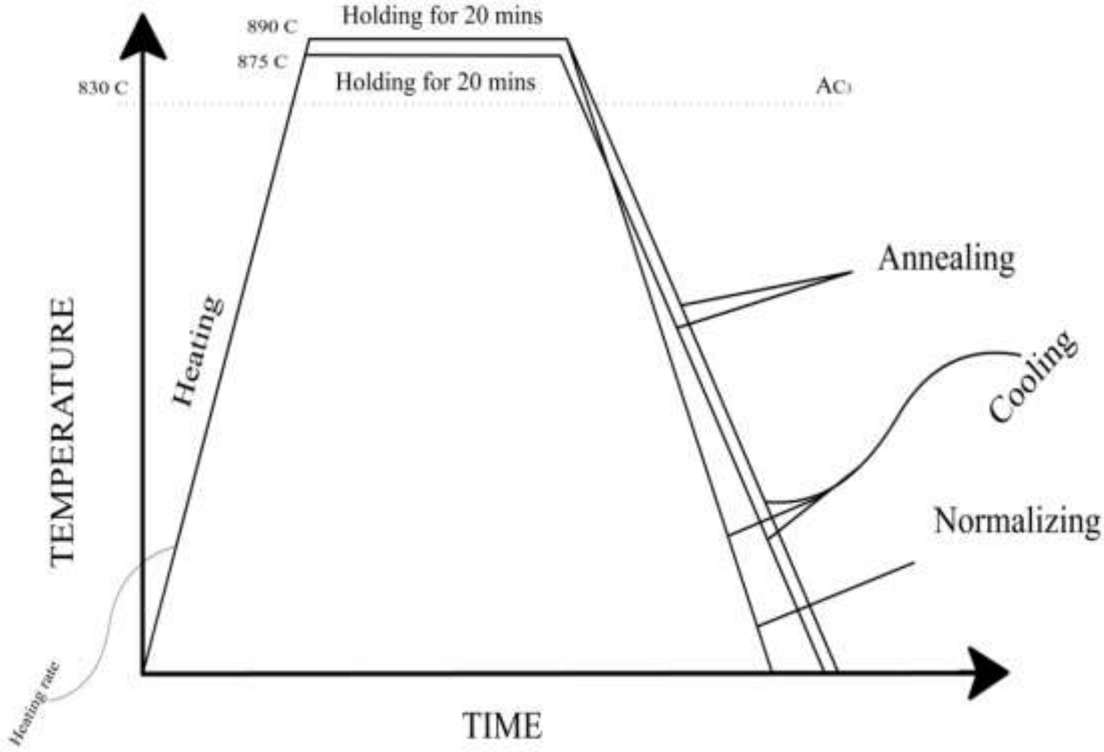

Fig 1: Heat treatment cycles of B.S 4449:2005 Samples

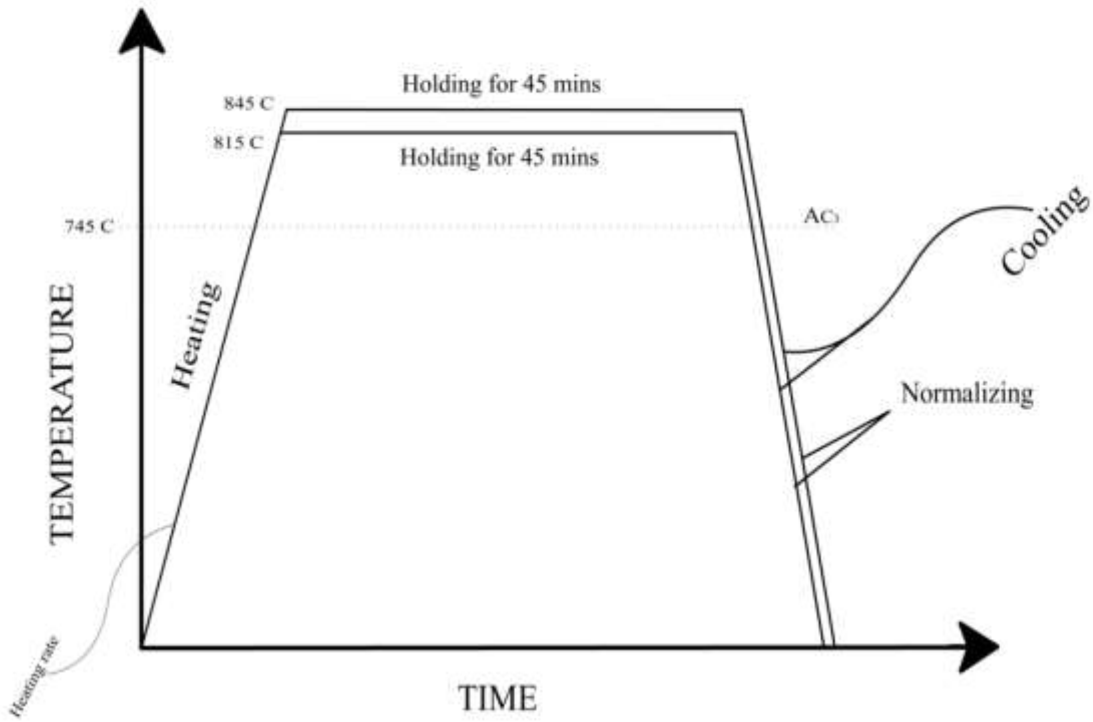

Fig 2: Heat treatment cycles of AISI 1060 Samples

3. 4. 1. Volume Fraction

Volume fractions of all the tests specimens are measured through point count method (Vander Voort, 1984).

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 890	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 (ASTM E112, 2010). 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 890	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 (ASTM E112, 2010). The ferritic grain sizes of all test specimens are shown in the Table 3.

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 890	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 (ASTM E112, 2010). 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 890	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

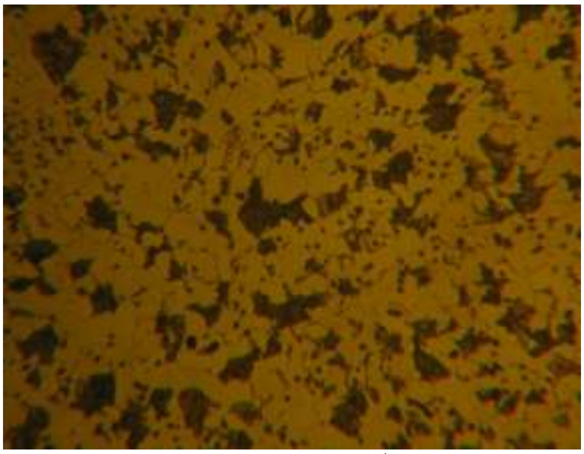

Fig 3: Annealed (875 °C) B.S 4449:2005 sample microstructure. Original magnification: 400x

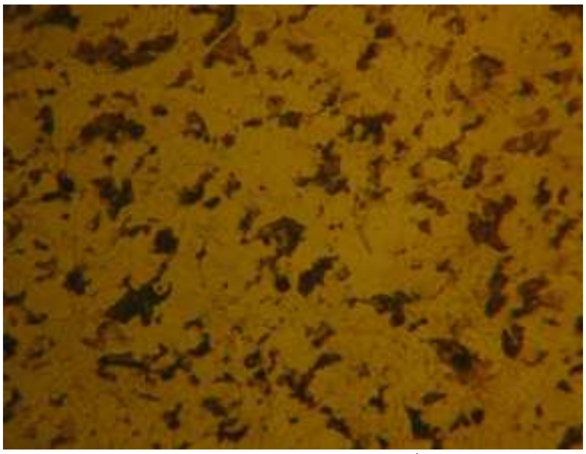

Fig 4: Annealed (890 °C) B.S 4449:2005 sample microstructure. Original magnification: 400x

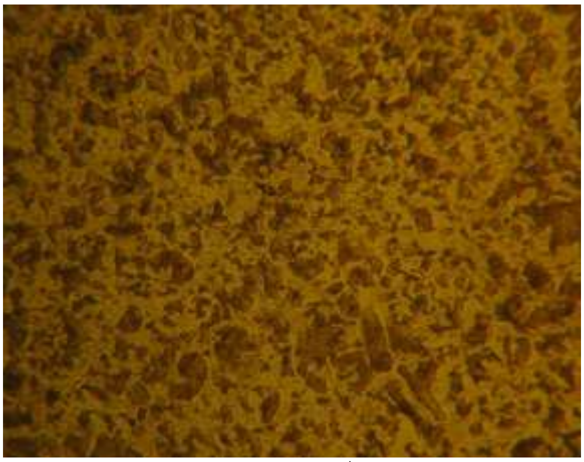

Fig 5: Normalized (890 °C) B.S 4449:2005 sample microstructure. Original magnification: 400x

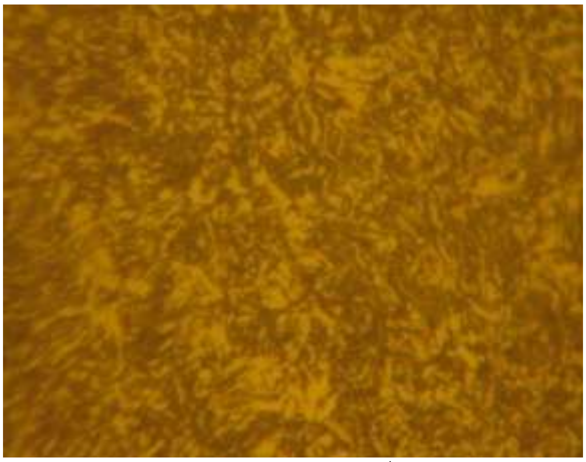

Fig 6: Normalized (815 °C) AISI 1060 sample microstructure. Original magnification: 400x

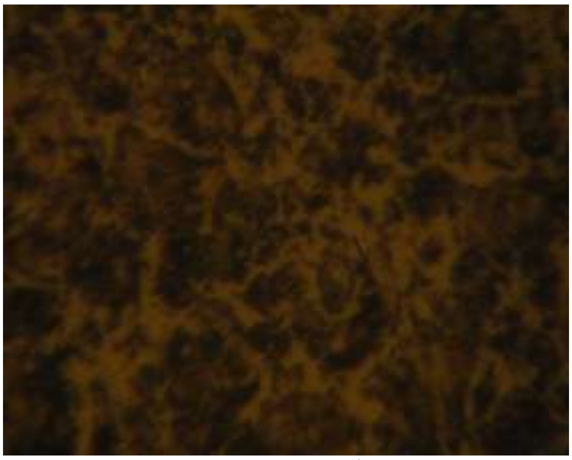

Fig 7: Normalized (845 °C) AISI 1060 sample microstructure. Original magnification: 400x

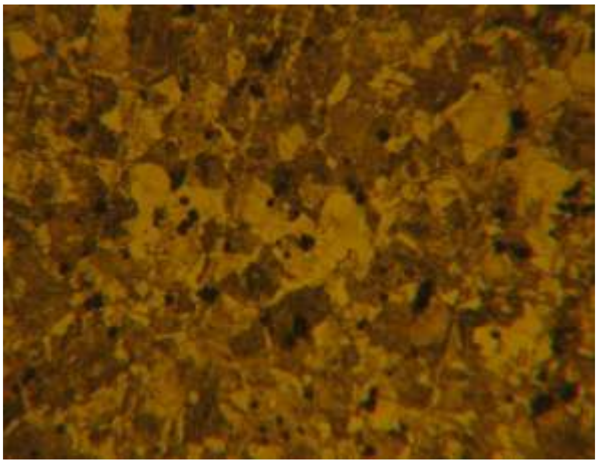

Fig 8: Hot Rolled AISI 1060 sample microstructure. Original magnification 400x

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 pearltic grain sizes with their relative volume fractions. This relationship is given by,

$$G_{avg} = V_f G_f + V_p G_p \quad (5)$$

Or,

$$G_{avg} = V_f G_f + (1 - V_f) G_p \quad (6)$$

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,

$$l = l_f V_f + l_p V_p \quad (7)$$

Or,

$$l = l_f V_f + l_p (1 - V_f) \quad (8)$$

Where,
l= Mean lineal intercept
l_f= Mean lineal intercept of ferritic phase
l_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 890	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 "l" and ASTM Grain Size G (ASTM E112, 2010), 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,

$$l = (\frac{\pi}{4} A_{avg})^\wedge ½ \quad (9)$$

Where,
A_{avg}= Average Grain Area of Circular Grain

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

$$(A_{avg})^\wedge ½ = V_f(A_f)^\wedge ½ + V_p(A_p)^\wedge ½ \quad (10)$$

Or,

$$(A_{avg})^\wedge ½ = V_f(A_f)^\wedge ½ + (1 - V_f)(A_p)^\wedge ½ \quad (11)$$

Where,
A_f= Area of the ferritic grain
A_p= Area of the pearlitic grain

5. Conclusion

In the context of equation number 5 and 7 it can be stated that the Average produced by the Abrams three circle intercept method (single phase grain size measurement method) when used over multi-phase structure is the weighted average of the grain sizes of the constituents present in the microstructure. It means in the average grain size the grain size of the constituent having larger volume fraction dominates.

It can also be declared in the perspective of equation number 10 and 11 that the square root of the average grain area of the grain of circular cross-section is equal to the sum of the products of square root of ferritic and pearlitic grain area with their relative volume fractions.

6. References

1) Vander Voort, George, P., 1984. Metallography Principles and Practices , New York: McGraw Hill.
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3) ASTM Standard E112, 2010, "Standard Test Methods for Determining Average Grain Size," ASTM International, West Conshohocken, PA, 2010, DOI: 10.1520/E0112-10, www.astm.org.