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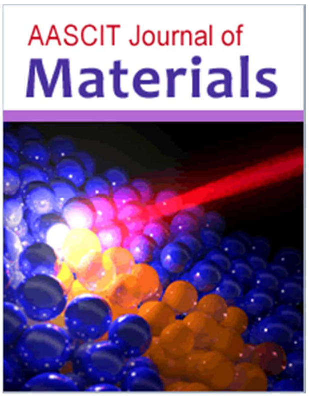

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The Effect of Hot Rolling on the Tribology of Ductile Cast Iron

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Abstract
Important applications of graphite bearing ferrous metals such as graphite steel and iron are wear - resistant ones. In these work, The ductile cast iron samples were hot rolled. The hot rolled ductile cast irons were subjected to double annealing by heating to 900°C and holding for 3hr then furnace cool to 700°C and holding at this temperature for 3hous then furnace cool to room temperature. The effect of cooling rate after rolling on the microstructure of rolled DCI and wear characteristics were determined. The hardness and the wear resistance of hot rolled ductile cast iron were significantly enhanced, the maximum rolling reduction percentages at fast cooling rate (air cool) and slow cooling rate (furnace cool) were evaluated.

1. Introduction

Wear can be defined as the progressive loss of material from the operation surface of a body occurs as a result of relative motion at the surfaces[1],[2]. As wear occurs in a wide variety of industries, it is also an item causing major annual expense through construction industry specially bridges[3],[4]. The factors which affect wear are numerous such as the type and method of loading, speed, temperature and material, the lubricant type and quantity is considered as the most important factor beside the chemical nature of the environment. The variety of conditions makes the study of wear is very complex subject [5],[6].

Gray cast irons are widely used in applications where lubrication is not feasible[7],[8]. Graphite detached from the cast iron the result will be the generation of series of mico-voids and that is act as emergency reservoir for oil [9]:[11]. The resistance to wear is also influenced by the form of the graphite [12],[13]. A nodular form in D.C.I is superior to wear resistance and can be considerably improved by work hardening [14].

Some characteristics are beneficial if high resistance wear is required in ductile cast iron (D.C.I) such as:

1 Amount of graphite should be high
2 Bainitic structure of ductile cast iron[15].
3 Upper limits of the phosphorous content must be at 0.25%.
4 White iron have a full pearlitic matrix is recommended for abrasive wear applications [16],[17].

1.1. Wear and Rolled Ductile Cast Iron

The main application of the rolled ductile iron as building elements are the metal structures for bridges and tunnels [18],[19]. This category of building elements are subjected to different types of wears and frictions such as:

- Abrasive wear arises from the presence of gritty particles between the moving parts, the result is bad appearance scratched surface.

- Pitting arises in the parts from sub-surface fatigue cracks[20]: [22].
- Repeated sliding of the parts ultimately allows the start of very small cracks below the surface of the metal.
- Over load wear is resulted from high load and low speeds lead to rupture[23]:[26].
- Sapling is more destructive effect than pitting
- Corrosion wear take the from of pits of the surface [27].
- Rippling is caused by plastic yielding and characterized by a peculiar fish-scale pattern is the result of heavy sliding [28],[29].
- Burning the discoloration following oxidation and accompanied by loss of hardness is due to excessive friction resulting from either over load or over speed [30],[31].
- Scoring is indicated by tears in the direction of sliding due to welding and metal transfer.
- Interference wear has constructional rather than operational origins. It can result from poor design or bad manufacture[32].

2. Experimental

2.1. Material

The ductile cast iron used in this work is obtained from El-Nasr Casting Company. The slab cut from centrifugal casting pipe with 1000 mm diameter and 10 mm thickness, which consider as the main commercial product in the Company. The chemical composition of the ductile cast iron is shown in table (1).

Table 1. *Chemical composition of D.C.I*

Contents	C	Si	Mg	S	Mn	Fe
Percentages %	3.68	2.1	0.0042	0.017	0.35	balance

2.2. Manufacturing & Treatment

2.2.1. Treatment Before Rolling

1. Slices were double annealed (L.H.T) to 900°C and hold for 2hr prior to furnace cooling to 700°C, then held at this temperature for 3hr before the furnace cooling to the room temperature.
2. Some of the slices were feritizing annealed (F.H.T) at 920°C for 30min then furnace cooled for 30min
3. Annealing: Full feritizing Annealing used to remove carbides and stabilized Pearlite by heat to 900˚C, holding long enough to dissolve carbides, then cooling at a rate of 85˚C/h to 705˚C, and still air cooling to room temperature. It improves low temperature fracture resistance but reduces fatigue strength.

2.2.2. Preheat Before Rolling

The L.H.T specimen is soaked at 950°C for one hour before rolling, while the F.H.T specimen is soaked at 900°C for one hour before rolling.

2.2.3. Rolling Process

Rolling was carried out on the slices in the circumference direction of the pipe by using a laboratory two - high reversing mill with 320mm diameter rolls and 450mm length. The slices were heated to a temperature range between 900°C and 950°C then soaked for one hour at this temperature. The rolls speed was 25m/min. Reduction in cross sectional area was carried out on 2 to 4 passes. Some of the rolled strips were air cooled A.C, while the others were furnace cooled F.C at 700°C. Table (2) shows rolling and preheat conditions of ductile Cast Iron

2.2.4. Heat Treatment

All specimens were double-heat-treatment annealed (DHTA) by heating in the muffle furnace to 900°C :910°C and holding for 3hr then furnace cool to 700°C and holding at this temperature for 3 hours and then furnace cool to room temperature.

Table 2. *Rolling and preheat conditions of ductile Cast Iron*

Specimen Number	Before rolling			After rolling		
	FHT	LHT	Soaking Temperature ℃	Hot Rolling Reduction %	Cooling rate (After rolling)	Rate Sec-1
11	XX		900	36	A.C	7.82
31	XX		900	42	F.C	8.68
32	XX		900	50	F.C	10.06
42	XX		900	26	F.C	6.13
43	XX		900	26	F.C	6.13
52		XX	950	46	F.C	9.23
53		XX	950	44	F.C	9.11
54		XX	950	50	F.C	10.06
62		XX	950	51	F.C	10.35
63		XX	950	48	F.C	9.75

2.3. Metallographic Examination

The specimens were prepared for examination first by grinding on different grades of silicon carbide "SiC" papers coarse grinding followed by fine grinding at 180,240,320,400,600,800,1000 and 1200 finally polishing was conducted with Alumina powder (3μm) size. The details of the microstructure were revealed after etching by standard etching solution of the alloy. All specimens had to be etched and polished several times to obtain best results and to produce a uniform level of sample examination. The surfaces of the samples before and after rolling and heat treatment were examined using an Olympus optical microscope Model BHM at selected magnification. The details of the microstructure were revealed after etching in 3% nital solution. The etching process was done by emerging the surface of the samples in nital solution. Specimen must be etched and polished several times to obtain best results and produce a uniform level of graphite matrix.

2.4. Mechanical Test

2.4.1. Hardness

The hardness of the specimens were measured by using Vickers testing machine at 15kg. Each hardness value is an average of 5 readings at least with scatter $\pm$ 4%.

2.4.2. Friction & Were Testing

The test was carried out in normal atmosphere include weighing the test specimen before and after test for assessing the wear properties in such contacts, pin-on disc wear test machine are used in this work. The tested specimen was held in sliding contact with rotating hardned alloy steel (Mn- Cr) disc with hardness (HRC65). The test specimen is mounted on to holder which was designed for easy change of pin (tested samples). The normal load range (0.2 - 3kg) is applied by dead weight at the end of level to cause the actual normal applied load on the test specimen to increase by a factor (liver ratio=2.75). At the end of loading beam there was a counter weight for oppose the beam weight, so the applied forces on the specimen come from the applied dead weight only cause a sliding speed ranges from (0.12:1.31) m/sec applied for 10min. The friction force between the vertical stationary specimen and rotation hardened steel disc was measured by strain gauges fixed on a cantilever attached to the tribo-testing machine from the signal, strain gauges was fed through an electric circuit F10MK11. Digital strain bridge reading are calibrated to read frictional force value by applying known dead weight later on the arm. The effect of Brinell hardness number of different specimen on properties are recorded.

The coefficient of friction is determined by:

$$U = \frac{F}{N} \tag{1}$$

F is the friction force.
N is the normal load.
U is the coefficient of friction
The wear volume is calculated from the relation

$$V = \frac{w}{\rho} \tag{2}$$

W is the wear weight the difference in weight of specimen before and after test .

ρ is the density of D.C.I equals to 7.2gm/cm^3.
The sliding distance calculated from the relation

$$L = 2\Pi rn \tag{3}$$

r is the mean radius of the rotating disc.
L is determined to be 78.5m (sliding distance)
n is the number of revolution
The following relation is used to calculated wear coefficient:-

$$V = K\frac{LW}{3P} \tag{4}$$

V the volume removed by wear from the surface.
K The wear coefficient.
L Length of travel.
W The normal load.
P The Indentation hardness of the softer body.
Liver ratio = 2.75

3. Results & Discussions

3.1. Microstructure

The microstructure features at different conditions before rolling were evaluated, figure (1) shows metallographic representation of as-cast ductile cast iron specimens, the microstructure of the alloy was studied, the microstructure consists mainly of pearlite and graphite nodules in ferritic matrix. The ferrite was free from sub-boundary structure, the high cooling rates achieved by centrifugal pipe casting process was responsible for the existence of cementite with ferrite in some areas of the matrix. The pearlite volume fraction was recorded at 23.81%.

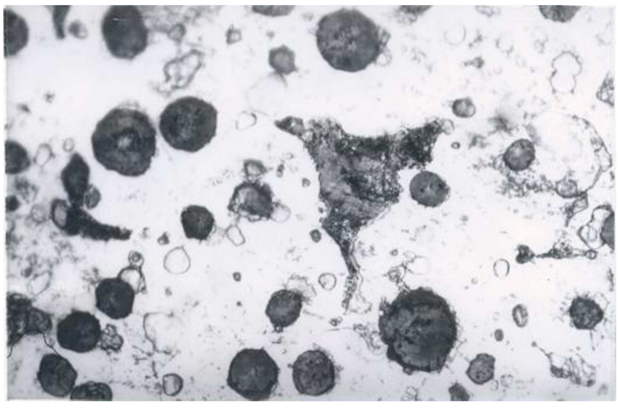

***Fig. 1.** As-cast ductile cast iron specimen*

3.1.1. Full Feritizing Annealing as Received (F.H.T)

The foundry heat treaded (F.H.T) annealing process was done, the microstructure constituent of these sample was shown in Figure (2), which is carried out after casting. The structure consists of graphite, pearlite (5%) and ferrite but with sub boundaries. Full feritizing Annealing used to remove carbides and stabilize Pearlite.

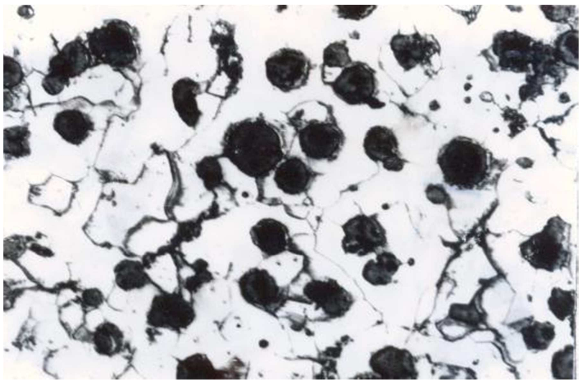

Fig. 2. Structure after foundry heat treaded (F.H.T) full feritizing annealing

3.1.2. Double Annealing LHT (DHTA)

The sample treated in the lab by (DHTA) was shown in figure (3), which represents a double annealing cycle lead to decomposition of all cementite and produce nodules impeded in full ferritic matrix which increases workability. It was necessary to preheating all samples in the range from 900°C to 950°C to produce adequate ductility for rolling and achieve fully austenite structure.

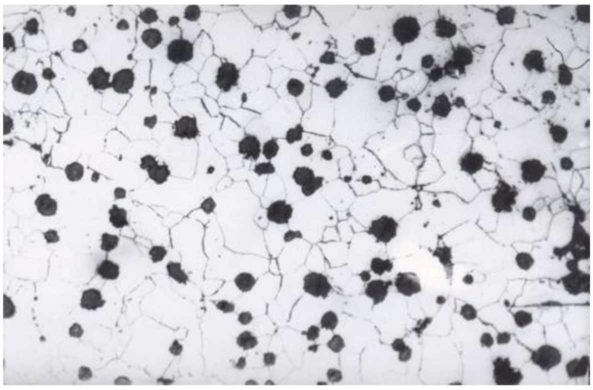

Fig. 3. Structure of ductile cast iron after double annealing cycle

3.1.3. Furnace Cool Specimen After Rolling

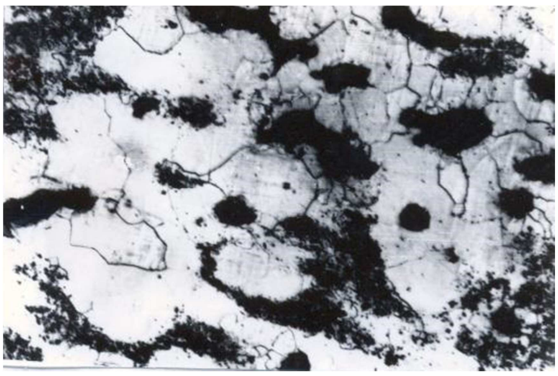

Fig. 4. DCI after rolling reduction furnace cool (before heat treatment)

Fig. (4) shows microstructure of hot rolled and then furnace cool specimens, it was deformed by different amount of reduction, graphite is deformed in the rolling direction, further increase in the amount of reduction lead to progressive elongation of graphite accompanied with decrease in the average thickness of the ferrite envelope. Furnace cooling creates sub-boundaries in ferrite while the amount of pearlite decreases, further increase in the amount of reduction more than 40% leads to crumble graphite where secondary graphite is formed all over the matrix.

3.1.4. Air Cool Specimen After Rolling

Figure (5) indicates microstructure of hot rolled specimen then air cooled, the nodules of graphite are enveloped in ferrite free from sub-boundaries and the remaining matrix is pearlite this emphasizes that air cooling rate is fast enough to ensure that carbon in solution of the austenite forms pearlite which causes raising of hardness, it can also be noted that graphite nodules are deformed by hot rolling into lens shaped disks ellipsoidal in plane which are flattened more as the amount of reduction increases.

Fig. 5. DCI after rolling Air cool (before heat treatment)

Fig (6) and figure (7) show the effect of heat treatment double annealing on hot rolled ductile cast iron, they represent the microstructure of heat treated specimens after rolling which divided into two main groups air cooled after rolling and furnace cool after rolling specimen respectively. Heat treatment produce full ferritic matrix the ferrite grain is elongated in the rolling direction, and also the graphite flattened as the amount of reduction increases. Heat treatment does not eliminate directionality (anisotropy remain) but only decompose the cementite which lead to reduce strength and improve ductility in order to enhance impact properties necessary for machining.

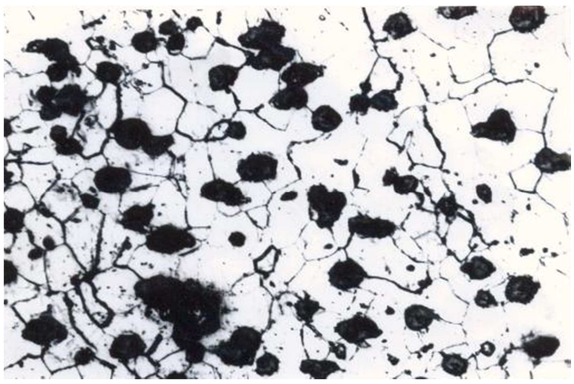

Fig. 6. DCI after rolling & heat treated AC FHT

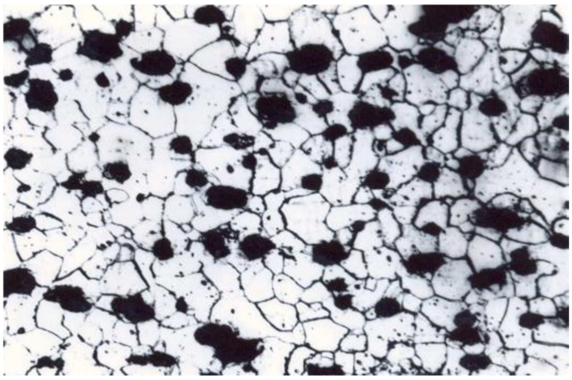

Fig. 7. DCI after rolling & heat treated FC FHT

3.2. Mechanical Properties

3.2.1. Hardness

The mechanical properties of the samples were recorded, table (3) shows the relation between Vicker hardness value and microstructure constitute before rolling at room temperature, each value was the mean of five (5) readings. Hardness value is strong function of the phases presented due to heat treatment process. The maximum value was recorded for as cast structure and the minimum one was recorded for the fully ferritic structure (L.H.T).

Table 3. The relation between micro-structure constituent of D.C.I and Hardness before rolling

Conditions	Vicker Hardness (VH)	Brinell Hardness (BHN)	Microstructure	Pearlite %
As Cast	211	201	graphite + ferrite + pearlite	23.8%
Laboratory heat treated (L.H.T)	166.67	158	graphite + ferrite + pearlite	5.1%
Foundry heat treated (ad received) F.H.T	86	90.5	graphite + ferrite + pearlite	0%

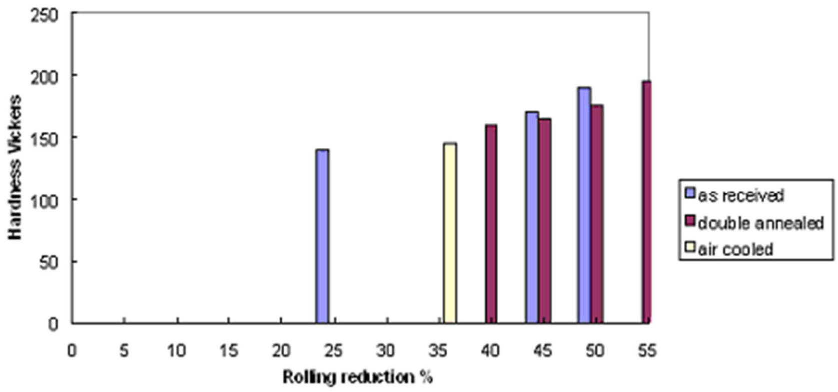

Fig. 8. The effect of reduction percentage during rolling on hardness

The correlation between the Vickers hardness of the rolled specimen and the amount of total reduction by rolling is shown in figure (8). It is clear that hardness increases by increasing the amount of reduction by rolling which may be attributed by the accumulative strain hardening effect.

The manufacturing condition include the type of heat treatment cycle has significant effect up on hardness, table (4) shows The relation between manufacturing and rolling conditions of D.C.I on Hardness. The air cooled specimens have always higher hardness value than that of furnace cooled specimen ones. In case of air cooled specimens the rate of cooling was higher. The double annealing is lower the hardness value due to the formation of soft fully ferritic matrix as result of double annealing process.

Table 4. The relation between manufacturing and rolling conditions of D.C.I on hardness

Specimen Number	Treatment Before rolling	Cooling rate (After rolling)	Hot Rolling Reduction %	V.H	B.H.N
11	F.H.T (as received)	A.C	36	147	140
31	F.H.T (as received)	F.C	42	165	156
32	F.H.T (as received)	F.C	50	183	174
42	F.H.T (as received)	F.C	26	140	133
43	F.H.T (as received)	F.C	26	140	133
52	L.H.T	F.C	46	165	156
53	L.H.T	F.C	44	162.5	154
54	L.H.T	F.C	50	174	166
62	L.H.T	F.C	51	177	168
63	L.H.T	F.C	48	173.5	164.5

3.2.2. Friction and Wear

The different wear and friction characteristics are determined by pin on desk technique, digital strain bridge reading are calibrated to read frictional force value by applying known dead weights laterally on the arm, figure (9) shows the calibration curve of the digital strain bridge.

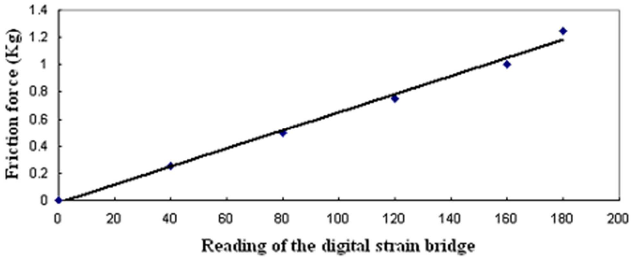

Fig. 9. *The calibration curve to read friction force value*

The particles of graphite were deposited from the matrix on the surface of hardned alloy steel disc work as dry lubricant. The wear tracks are formed on polished tested specimens. After subbing against rotating hardned alloy steel disc. The grooved appearance of the tracks indicates the breaking of the hardned layers and suggests many wear mechanisms involved. The surface damage is less pronounced with low surface hardness as may be noticed by comparing various types of damage to sliding surface have been observed such as removal of graphite particles from matrix of test specimens reduced deformation micro cutting and tearing in depth, so the loose of graphite particles is the source of dry lubrication, all results are recorded in table(5). The wear tested specimens at constant load and constant sliding speed is dependent on the hardness and microstructures of tested specimens, during sliding deformation of surface may occur,

Table 5. *Wear properties data calculated*

Specimen Number	Hot Rolling Reduction %	Wear Weight	Wear Volume	Wear Rate	Wear coefficient
11	36	1.7783	0.2470	3.1465×10^{-4}	1.0777×10^{-5}
31	42	1.6143	0.2242	2.8561×10^{-4}	1.0036×10^{-5}
32	50	1.8641	0.2589	3.2981×10^{-4}	1.0264×10^{-5}
42	26	1.6321	0.2267	2.8879×10^{-4}	1.00195×10^{-5}
43	26	1.2418	0.1725	2.1475×10^{-4}	0.8798×10^{-5}
52	46	1.3126	0.1823	2.3223×10^{-4}	0.89869×10^{-5}
53	44	1.8923	0.2628	3.3478×10^{-4}	0.64032×10^{-5}
54	50	1.6141	0.2242	2.8561×10^{-4}	1.04807×10^{-5}
62	51	1.5943	0.2214	2.8204×10^{-4}	1.05380×10^{-5}
63	48	1.6068	0.2232	2.8433×10^{-4}	1.04972×10^{-5}

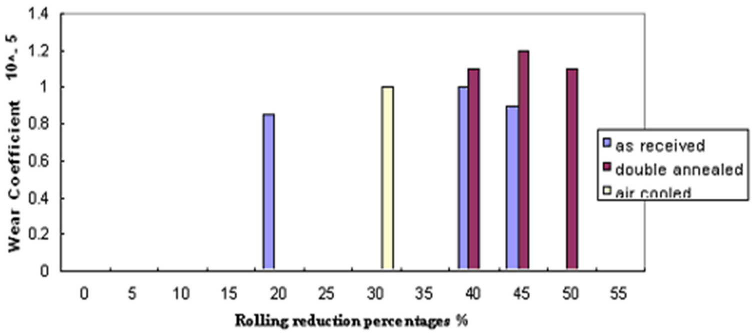

Fig. 10. *The effect of reduction percentages on friction coefficient at different conditions*

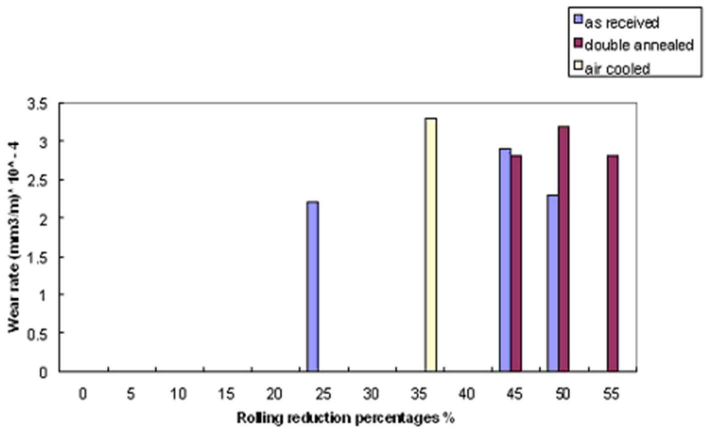

Fig. 11. *The effect of reduction percentages on wear rate at different conditions*

Gray cast irons are widely used in applications where lubrication is not feasible, because they exhibit low wear rates and can be used as sliding against themselves (35). During the initial sliding of graphite. The basal planes of graphite shear appear and provide a continuous source of a solid lubricant due to the crystallographic structure, Graphite detached from the cast iron the result will be the generation of series of mico-voids and there is act as self lubrication, figure (10) and figure (11) show the effect rolling reduction percentage on the wear coefficient (coefficient of friction) and wear rate respectively.

The fraction behavior of different conditions was function on hardness, figure (12) shows the relationship between the hardness and the friction coefficient of the annealed specimen of hot - rolled ductile cast iron which vary with the hardness of the tested specimens.

The wear resistance is also influenced by the graphite form. nodular form in D.C.I is superior to wear resistance also can be considerably improved by work hardening due to rolling

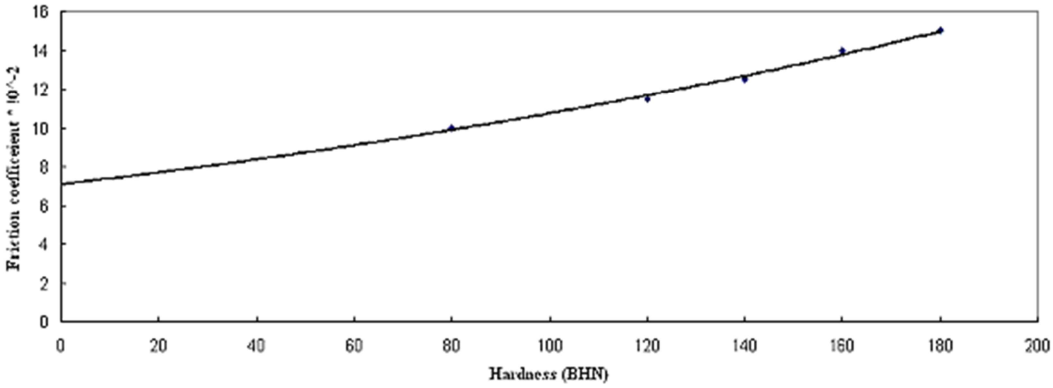

Fig. 12. *The effect of hardness on the coefficient of friction*

The wear coefficient K of hot rolled ductile cast iron is similar to that of tool steel, So it is recommended for building elements in moving parts.

4. Conclusions

1. Rolling of ductile cast iron can improve properties in the rolling direction such as hardness, wear and friction.
2. Hardness increases linearly with increase of the percentage of rolling reduction due to strain hardening.
3. The pearlite percentages have significant effect on hardness and wear
4. Ferrite grain size was dropped sharply with increasing rolling reduction percentages which may be attributed to enhance of nucleation process.
5. Friction coefficient decrease with increasing of reduction percent which may be attributed to stress concentration in vicinity of graphite nodules that work as self lubricant element.
6. Superior wear properties were relate to rolling of D.C.I because graphite work as a dry lubricant minimizing wear.
7. Rolled ductile cast iron consider as more economical relative to carbon steel so it may be recommended in construction and building applications

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