1.1 **Metallurgy of gray cast iron**:

Most of industrial automobiles companies produced the brake rotor part from a grey cast iron. The cast iron material differ from standard steels by having significantly higher carbon (C) and silicon (Si) contents. Steel typically has less than 1.2 weight percent (wt. %) carbon and little or no silicon, while the carbon content in cast irons typically ranges from 2.5 to 4.5 wt. % C and 1 to 3 wt. % Si. Cast irons also often have higher sulphur (S) and phosphorus (P) contents, while manganese is an important additive in both metals. The extra carbon and silicon in cast iron is added primarily to lower the melting point of the metal. Cast irons easy to cast into complicated shapes such as pipes and fittings. Sulphur, by contrast, is an unintentional addition to iron or steel and, especially in more modern pipes, is either removed or controlled by the addition of manganese. Sulphur without manganese tends to form brittle iron sulphide at the boundaries of the grains in the metal. This is more of a problem in steels, where the inclusions will cause cracks during rolling and other forming, but can also be detrimental to cast irons [Dippenaar, 1996].

The basic material of grey cast iron consists of metal and graphite flakes. The size and the shape of the graphite flakes and the exact type of metal depend on the manufacturing process. The metal in cast irons can be either ferrite (almost pure iron) or Pearlite (alternating bands of ferrite and iron carbide in a single grain). Very slow cooling tends to produce very large graphite flakes and Ferrite, moderate cooling produces Pearlite and somewhat smaller flakes and very quick cooling produces Ferrite and very fine flakes. The tendency to produce Pearlite or Ferrite is also affected by the alloying elements in the cast iron. The shape of the graphite flakes is also affected by the cooling rate and other processing [Hong Jiang, 2003].

The creation of graphite flakes as cast iron cools is unavoidable, but it is also detrimental to the strength of the produced structure such as (brake rotor). Flat flakes act as natural crack former, which means that grey cast iron tends to produce brittle fractures that travel along the flakes [Sun, G.X., 1990]. The grey colour of alloy's fracture surface that gives it its name is produced by these flakes, not by the metal grains [ASM, 1985]. Modifying the shape or size of these flakes can improve the material's mechanical properties. The most extreme example is ductile iron, where the addition of small amounts of magnesium causes the graphite to form small spheres rather than a continuous network of flakes. As a result ductile iron is both stronger and tougher than grey cast iron while still being readily castable.

3. Experimental procedure:

The aim of this work is to study the effect of heat treatment on thermal conductivity and mechanical properties of gray cast iron used in the manufacturing of brake rotor in automotive industry. Now, in order to accomplish this aim, the following procedure has been preceded:

1. Production of gray cast iron samples.
2. Application of multi-types heat treatments such as:
   a. Annealing.
   b. Normalizing.
   c. Quenching and tempering.
3. Examination of thermal conductivity for the samples resulted from the above heat treatments.
4. Evaluate the mechanical properties such as hardness and tensile strength.

3.1 Materials used

The average chemical composition of the gray cast iron samples is given in the following table (3.1). This chemical analysis is obtained from samples prepared by melting a sufficient scrap of brake rotors that made from a gray cast iron alone, mixed in furnace to simulate the actual practice conditions and then pouring into a sand mold. Samples for chemical analysis and heat treatments were prepared from the as cast products under coolant machining in the Ministry of Sciences & Technology.

3.2 Heat treatment practices

The following heat treatment practices are adopted:

1. Annealing: It is the process of heating to 900°C and cooling in the furnace.
2. Normalizing: It is the process of heating material to above 900°C (AC_3 + about 40°C) and cooling in still air.
3. Quenching + tempering: In this process, the material heated to 900°C, cooling in oil to room temperature, then tempered to 500°C.

3.3 Thermal conductivity examination:

Thermal conductivity has been conducted for all samples produced from the heat treatments steps. Thermal conductivity was measured by the using of stationary axial heat flow (i.e. Phrus lee method). Samples of heat conductivity measurements are of (40mm diameter) with the thickness of 3 mm. the thermal conductivity factor (K) was measured by applying a heat source on the one side of the sample, while the other side subjected to a heat sink. The radial heat loses are minimized by a heat insulator (i.e. high density Teflon material). The time of test is recorded up to 45 min [ASTM, 2000].

3.4 Mechanical Properties examination:

Examination of mechanical properties is very important for engineer and metallurgist. This examination is so important in this work where the produced material are candidate to work as a brake rotor in an automotive industry. The hardness and tensile strength have proved to give reliable indications of the ability of the material to perform certain types of duties. The main purpose of these properties is to check whether the material used in the brake rotor manufacturing meets the requirements or not.

1. Hardness Tests: A Brinell hardness test used to indicate the surface of the metal by hardened steel ball (10 mm) diameter under a load of 30 D^2. This test has been done in the following conditions:

   a. As received specimen.
   b. As cast specimen.
   c. Annealed specimen.
   d. Quenched and tempered specimen.

2. Tensile test: an ultimate strength and elongation could be achieved by tensile testing with the using of flat shape specimen as shown in the figure (3.1). This figure indicated the dimensions that adopted in this work [Hand book of Mechanics, 1985].

3.5 Microstructural examination:

An optical examination has accompanied each step of work in order to observe the fine structural details under suitable magnification and using the following formula according to [ASM ,1977]

(35%) HCl + distilled H_2O

4. Results and Discussion

Figure (4.1 and 4.2) shows the optical microstructure of as received and as cast material that adopted in this work. The cooling rate during the solidification of the samples used in this work is almost constant. When the temperature drop down the (Fe-graphite) commences in the liquid. These dendrites as shown in figure (4.1-a) becomes strengthening. The flake graphite is the characteristics of gray cast iron; the existence of Silicon in percentage of (3.02) promotes its formations. The as received material seems to be solidified under moderate cooling rate, so that; their distribution tends to be interdenderitic. The matrix of samples above is a pearliteic-ferritic. Knowing that, the matrix microstructure depends mainly on the chemical composition as well as the heat treatments cycle.

Figure (4.1-b) as shown below; represent an optical microstructure of the material in as cast conditions, where the cooling rate is high enough to give finer flake graphite. It is obvious from that a uniform distribution of randomly oriented graphite flakes which promotes the interdenderitic distribution. The existence of phosphors in the received material (brake rotor scrap) promoting the formations of the so called Phosphors eutectic which is called Steadite.

4.1 Effect of annealing on mechanical properties:

In this type of heat treatment practices, the samples are heated to 900ºC to get an austenite phase, this phase represent a well known solid solution of Fe and C. Then cooling in furnace indicate a very low cooling rate, this cooling rate allowed or give a sufficient time for the carbon atoms to diffuse. The diffusion of carbon atoms promotes the decomposition process of carbon on the graphite flakes which in turn affect the matrix resulted structure. The matrix now becomes almost ferritic than pearliteic structure (see figure ((4.2) a and b).

4.2 Effect of Normalizing on mechanical properties:

This type of heat treatments including the heating of specimens to 900ºC in order to get an austenite phase, then cooling in air where the cooling rate is modified than that adopted in the case of annealing practices. This cooling rate is fast enough to prevent the diffusion of carbon atoms. That means the decomposition process of carbon on the graphite flakes is less than that occurs in annealing process. This will result in more Pearlite on the account of ferrite as shown in figure (4.3) that shows the resulted microstructure in different magnifications. However the area adjacent to the graphite flake will experience carbon decomposition and ferrite will result around the flakes. It is clear from the microstructure above, that the normalizing process will give more Pearlite which is stronger than ferrite because of cementite layers inhibited in it. So the mechanical properties of normalized cast iron is greater than that of annealed (i.e. greater UTS and hardness and lower elongation as can be seen in table (4.1) and figures (4.5) and (4.6). These results are in time with the expected hardening of normalizing cycle. This is due to the increased amount of Pearlite in the matrix and also due to the refinement of the grain structure. Both of which can affects the hardness.

4.3 Effect of quenching & tempering on mechanical properties:

The third process is the(quenching + tempering) which is the process of increasing the hardness of the cast iron by heating the metal to 900ºC and rapid cooling in oil. The quenching process resulted in producing Martinsite which is a super-saturated solid solution of carbon in BCT (body centered tetragonal) but because of the drastic coolers and entrapment of carbon in iron crystal lattice. The martinsite is very hard, very brittle and is of little use in industry. Therefore, another heating cycle is needed to precipitate carbon out of Martinsite as (Fe_3 C) by a process of tempering, (see figure (4.4) that shows the resulted graphite flakes in a tempered martinsitic matrix).

Tempering process have been conducted at 500 ºC then samples cooled in air, the ductility's as shown in figure (4.6) has increased in the tempered martinsite more than the samples of annealed and normalized conditions.

The increasing of hardness is very useful in the modification of brake rotor wear resistance since the rotor subjected to almost continuous contacting by the brake pads. Now the improvement in hardness that accompanied with a noticeable improvement in ductility can gives a supporting for the using of this type of heat treatments in the manufacturing of an automotive brake rotor where an impact resistance is high due to a modified ductility that accompanied with a high hardness and ultimate tensile strength.

4.3. Effect of heat treatments on thermal conductivity

Thermal conductivity values of samples produced (i.e. metallographic phases) of cast irons are presented in Table (4.2). It can be seen that a ferritic microstructure has higher thermal conductivity than Pearlitic and also that cementite matrix which in turn can lower the cast iron thermal conductivity. Unfortunately ferrite has poor mechanical properties with excellent thermal conductivity. Parallel to the graphite basal plane the thermal conductivity is high and, in this condition, is the phase with highest thermal conductivity. So, a graphite shape that eases the thermal conductivity along the basal plane must result in maximum thermal conductivity.

5. Conclusions:

According to previous results and discussions, the following can be concluded:

1. Mechanical properties of gray cast iron depend mainly on the microstructure type of matrix and also to the distribution of graphite flakes.
2. During normalizing heat treatment, the decomposition process of carbon on the graphite flakes is less than annealing process. However the area adjacent to the graphite flake will experience carbon decomposition and ferrite will result around the flakes.
3. The increased amount of Pearlite in the matrix that accompanied with the refinement of the grain structure lead to an improvement of mechanical properties.
4. The quenching followed by a tempering process at 500°C can give a better UTS, elongation at the same numbers of hardness.
5. Thermal conductivity which is the prime requirements in brake rotor applications also improved according to the microstructure evolution.

Table (3.1): Average chemical composition of gray cast iron samples

Element	C	Si	P	Mn
wt%	3.268	3.087	0.046	0.03

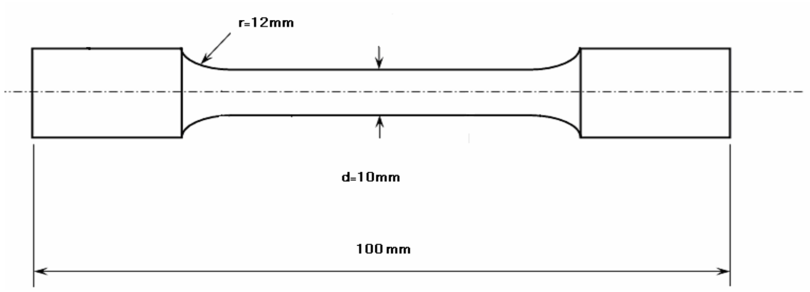
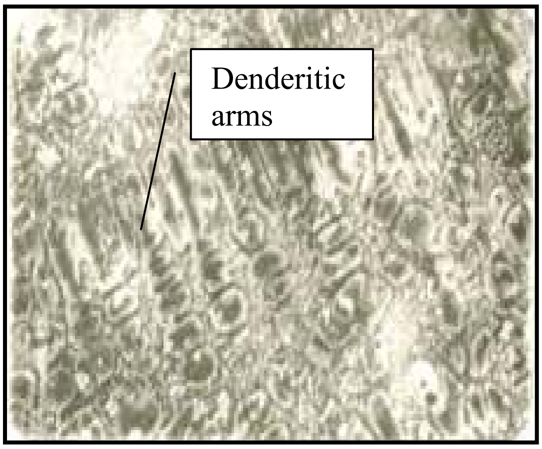
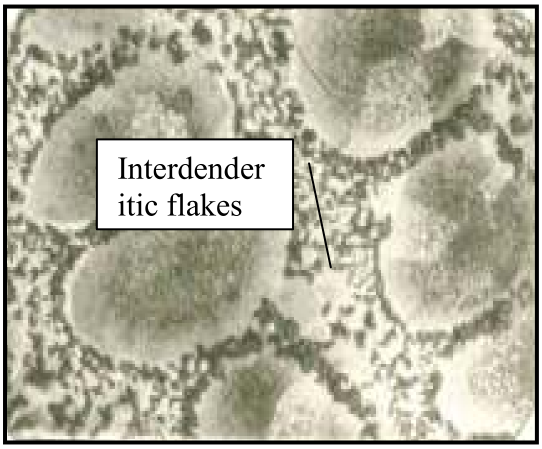


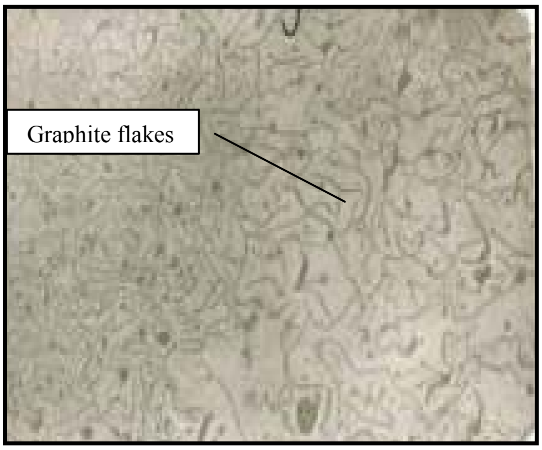
Figure (3.1)
Tensile test specimen dimensions

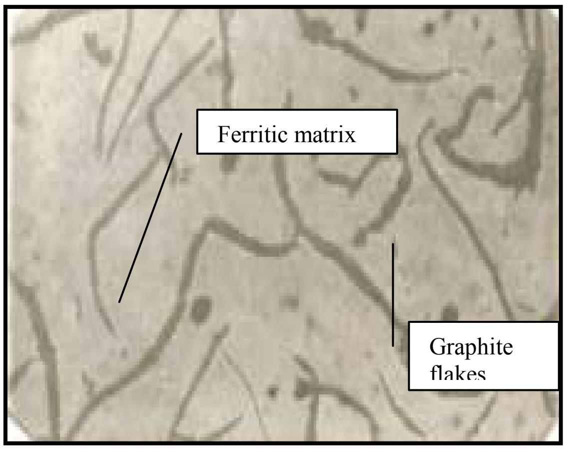




(a) (b)

Figure (4.1)
Optical microstructure of gray cast iron samples: a. as received (200X) , b. as cast, (400X)

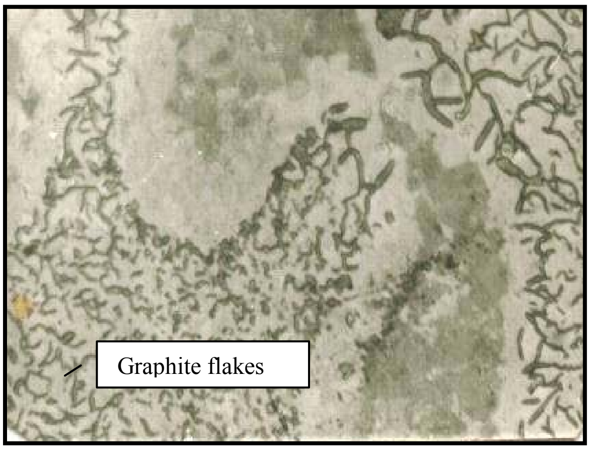




(a) (b)

Figure (4.2)
Optical microstructure of gray cast iron samples in annealed conditions:
a. 200 X and b. 500 X.

(a)

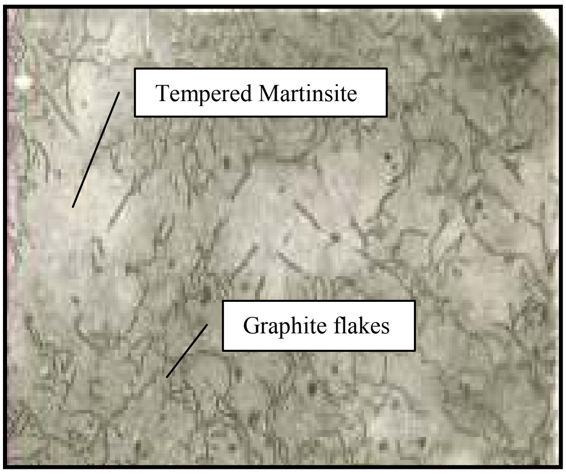


(b)

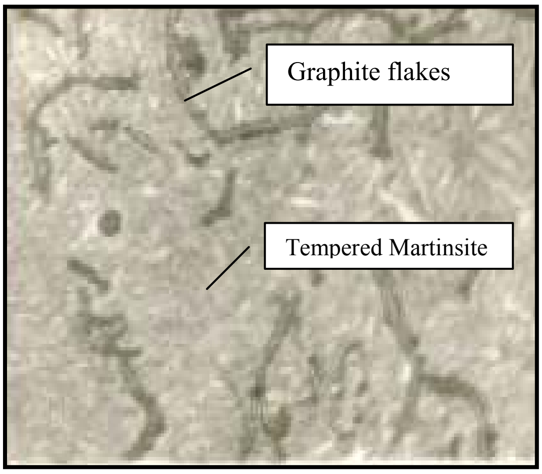
Figure (4.3)
Optical microstructure of gray cast iron samples in normalized conditions:
a. 200 X and b. 500 X

Table (4.1)
Results of hardness test

Code no.	Type of heat treatment	BHN
A	As received	193
B	As cast	180
C	Annealed	131
D	Normalizing	229
E	Quenching + tempering	249



(a)



(b)

Figure (4.4):Optical microstructure of gray cast iron samples in quenched and tempered conditions: a. 200 X and b. 500 X.

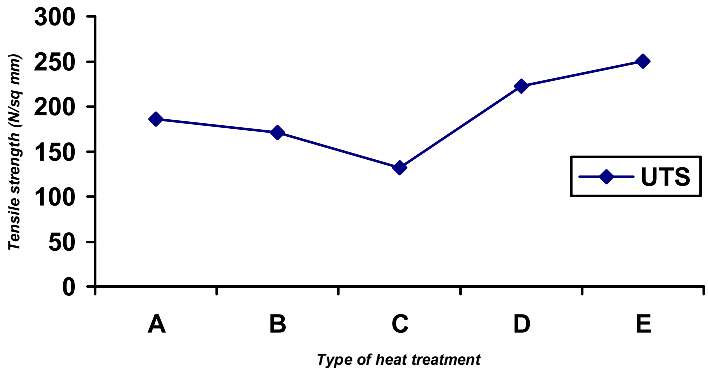


Figure (4.5)
Effect of heat treatment type on the ultimate tensile strength

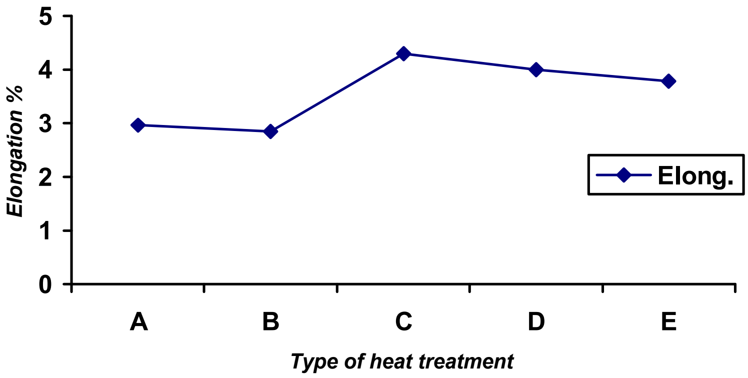


Figure (4.6)
Effect of heat treatment type on elongation

Table (4.2): Results of thermal conductivity measurements of produced samples from heat treatments

Code no.	Type of heat treatment	Resulted microstructure	Thermal conductivity (W / K.m)
A	As received	Pearliteic-Ferritic + graphite flakes	42.6
B	As cast	Pearliteic + finer graphite flakes	42.1
C	annealed	Ferritic + finer graphite flakes	48.7
D	normalized	Pearliteic + finer graphite flakes	44.2
E	Quenched + tempered	Tempered Martinsite + finer graphite flakes	41.8

REFERENCES

ASTM, " *Thermal Conductivity of Solids by means of the guarded-Comparative-Longitudinal heat flow Technique*", 2002.

American Society of Metals, 1985. American Society for Metals (ASM), Metals Park, Ohio 440073, USA, 1985.

C. R. Loper Jr., R. C. Voigt, J. R. Yang, and G.X. Sun, "*Electron Microscope in Studying Growth Mechanisms in Cast Irons*", AFS Transactions, 172 (1981), pp.529 542.

Dippenaar, R.J., Journal of the south Africa, Institute of mining and metallurgy, 5, 1996.

Hong jiang, Yiyong Tan, Junfery Lei" *Auto analysis system for graphite morphology of gray cast iron", Journal of automated methods of management in chemistry*, Vol.25, No. 4, pp. 87-92, 2003.

Handbook of Mechanics, Materials and Structures", (ed. A. Blake), New York, John Willy and Sons, 1985.

Lissa Wallis, Eddie Leonardo and Brain Milton," *Air flow and heat transfer in ventilated disc brake rotors with diamond and tear drops pillars*", Numerical heat transfer, part A, 41: pp. 643-655, 2002.

Sun, G.X. and Wang, Y.M., "*The role of dendrites and eutectics in the fracture of gray iron, Physical Metallurgy of Cast iron IV*, Preceding of Fourth International Symposium on the Physical Metallurgy of Cast iron, Tokyo, Japan, 1990.

S Y Buni, N Raman and S Seshan, "*The role of graphite morphology and matrix structure on low frequency thermal cycling of cast irons*", *S¯adhan¯a* Vol. 29, Part 1, February 2004, pp. 117–127. © Printed in India

T. AIp, A. A. Wazan and F. Yilmaz"*Microstructure-Property relationships in cast irons" The Arabian Journal for Science and Engineering*", Volume 30, Number 2B, October 2005.