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Evaluation of the effect of Annealing on the Microstructure and Mechanical Properties of Rolled Steel Products

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Abstract

This research work is focused on the evaluation of the effect of annealing on the microstructure and mechanical properties of rolled steel products. The material used for this research work includes mild steel round bar of dimension 30mm diameter and length 175mm. The mild steel round bar was divided into Sample A, Sample B, Sample C and Sample D respectively. Each of the samples was properly machined to the required shape using a lathe machine. Four samples of 55mm in length were used to produce round steel bar which was used for investigation of impact tests. The samples were observed for metallographic structural inspection. Subsequently, tensile strength test and impact test of the material were carried out. The results obtained reveal that annealing heat treatment influences the mechanical properties of the rolled steel. An improvement in ductility of materials was recorded. Above and beyond, the microstructure analysis results show that between the temperatures of 650^0C – 750^0C, there was no serious transformation despite the precipitation of the carbon. However, between 750^0C – 850^0C, serious transformation was recorded.

Keywords: Annealing heat treatment, rolled steel, microstructure, mechanical properties, transformation, ductility

1. Introduction

Generally, machining process of metals are very difficult, hence the need for heat treatment. Heat treatment soften the metal for easy machining operation (Ismail, et al., 2016; Oyejide, et al., 2917; Orhorhoro, et al., 2018). For instance, in metal casting, most metals usually have gases trapped in between its layers. However annealing such metal will help to remove the gases trapped in between its layers (Morrogh, 1982). Annealing is a heat treatment process that changes the physical and at times also the chemical properties of the material mainly to increase its ductility. It soften the annealed material, relieve its internal stress thereby refining the structure by making it uniform so as to improve its cold working properties (Isfahany, et al., 2011; Fadare, et al., 2011). Usually, annealing process involves heating the metal above its glass transition temperature, and maintaining the temperature over a specified period and then allowing it to cool. During annealing process, the cold-worked state of the metal is usually in higher internal energy than the un-deformed metal. Despite the cold worked dislocated cell structure is mechanically stable; still it is not thermodynamically stable (Al-Quran and Al-Itawi, 2010). However, with increasing temperature, the cold worked state becomes more unstable. A stage will reach when the metal eventually becomes soft and returns to a strain-free condition.

Annealing process of metals is very vital because it regain ductility to a metal which has been severely strain-hardened. Consequently, by interposing annealing process operations after numerous deformations of a metal, it is possible to recover its metallic structure to a great extent. The process of annealing is usually classified into three fairly distinct processes (Rajput, 2004): recovery, recrystallization, and grain-growth. Recovery phase of annealing heat treatment process deals with the restoration of physical properties of the cold-worked metal without any significant change in the microstructure (Rajput, 2004). The electrical conductivity of the metal increases rapidly as the lattice strain reduces appreciably. However, the properties that are adversely affected by recovery are those which are sensitive to point defects. For the strength properties which are controlled by dislocation, are usually not affected at recovery temperature, giving the clue the possibility of recovering completely the yield stress of a strain-hardened crystal without producing recrystallization.

Recrystallization process which usually has to do with the replacement of the cold-worked structure by a new set of strain-free grain is readily detected by the metallographic method and it is obvious by a decrease in the hardness or strength of the metal, thus an increase in ductility (Calister, 2007). It is of important to note that the density of dislocations decreases considerably on recrystallization thereby eliminating all effect of strain hardening. Moreover, the energy usually stored in cold work is the driving force for both recovery and recrystallization. Thus, if the new strain-free grains are heated at a temperature greater than that required for recrystallization to occur, there will be a progressive increase in grain size. Hence, the driving force for grain growth is the decreases in free energy which resulted from a decrease in grain-boundary due to an increase in grain size. Recrystallization process involves the nucleation of a strain-free region whose boundary can transform the strained matrix into strain-free material as it moves. However, in the growth of the boundary out from the nucleus, the dislocations are usually annihilated in the region swept through. Therefore, the moving boundaries must be in a high angled boundary so that there is a high degree of misfit to accommodate the dislocation.

For now, two distinct nucleation mechanisms have been recognized for recrystallization. First and foremost, the induced boundary migration where a strain free nucleus is formed as a result of one of the existing grain boundaries movement into its neighborhood leaving a strain-free recrystallized region behind. This boundary movement into the grain contains higher dislocation density in the local region. For the second nucleation mechanism, new grain boundaries are formed in region of sharp lattice curvature through sub-grain growth. Nevertheless, the mechanism seems to dominate at high strains with nuclei appearing at grain boundaries, twin boundaries, or at inclusion or second phase particles. The nuclei is form only in regions through which homogeneous deformation have been rotated, into an orientation that differ from that of the matrix. The six-matrix variable that influences recrystallization behavior include (Rajput, 2004);

i. Amount of heat prior deformation
ii. Treatment temperature
iii. Holding time
iv. Initial grain size
v. Composition and
vi. Amount of recovery prior to recrystallization.

Since the temperature at which recrystallization occurs mainly depends on the above variation, it is not a fixed temperature in the sense of a melting temperature. For a more practical consideration, a recrystallization temperature can be defined as the temperature at which a given metal or alloy in a highly cold worked state recrystallizes completely. The discrepancies that arise during the annealing process are usually between recovery and recrystallization. Recovery covers all the phases and the changes which do not involve the sweeping of the deformed structure by migrating high angle grain boundaries. The deformed crystal (or poly-crystalline structure) keeps its identity of which the density of the crystals detects and their distribution changes. For a special form of recovery to occurs, residual stresses resulting from metal working processes are removed by heat treatment.

Furthermore, when the stresses are long-range (i.e., approximately uniform over a long distance compared with the grain size), then the removal is termed stress relief. Also, in recrystallization, the crystal orientation of any region in the deformed material is altered more than once. The alteration resulted from results from the passage through the material of high angled grain boundaries. A population of a new grain growth is propagated usually along the boundaries of the deformed material, and these then grow at the expense of the deformed structure until it is all consumed. Thus, grain boundaries continue to move or migrate, but more slowly at this stage of cannibalism among the new population of grains is term “grain growth”. Typically, all boundaries tend to move to a uniform size area; however such movement is restricted to a minority of boundaries only so that a few grains grow very large at the expense of the rest (Rajput, 2004).

2. Materials and Methods

The material used for this research work includes; a mild steel round bar of 30mm diameter which was cut into four samples of length 175mm, a suitable measured length for tensile testing, and each of the samples were labeled as; Sample A, Sample B, Sample C and Sample D. Subsequently, each of the specimen samples was machined to the required shape using a lathe machine. Four samples of about 55mm in length was also cut from the round steel bar to be used for impact tests and was also labeled Sample A, Sample B, Sample C and Sample D. Lastly, four samples measured 40mm in length were used for metallographic structural inspection. The test for tensile strength and impact test of the material were carried out with the results recorded.

2.1 Annealing

The annealing process was carried out at temperature of recrystallization, grain-growth, and stress relief for samples A, B, and C. The three samples were subjected to heat treatment of 650^0C, 750^0C, and 850^0C respectively.

Sample A was annealed to temperature of 650^0C
Sample B annealed to temperature of 750^0C
Sample C annealed to a temperature of 850^0C,
Sample D served as the control experiment or specimen (as received).

Each of the samples (i.e., A, B, C and D) was annealed at different temperatures and left to cool in the oven for approximately 28 hours each. However, for the stress-relief stage, the samples were heated at relatively low temperature of 650^0C for a period of one hour and then allowed to cool in the oven. For recrystallization phase, the samples were heated to a temperature of 750^0C for about 1 hour. The samples used for grain-growth annealing was heated to a temperature of 850^0C for 1 hour and also left to cool in the oven. The annealing temperature at any of the phase was maintained mainly to avoid annealing at very low temperatures and equally to prevent remnants of the as-cast structure, thus avoiding rapid cooling in other to prevent stress from setting in.

Fig. 1 Annealed Tensile Test Specimen

2.1. Tensile Test

The steel sample was cut to the required length. A universal tensile testing machine was used to determine the tensile strength of the samples used in this research work. Loading was applied in a progressive increasing tensile pull until it eventually fractured. Before the test, the gauge lengths were marked out on the specimens and properly measured. The length and weight of the samples were taken using a vernier calipers and a precision balance scale. The samples were griped and loaded till yield point was reached, and the stress and corresponding strain obtained at this point was recorded. However, the loading (tensile pull) continued till the maximum loading point was reached. At that point, the stress and the corresponding strain were recorded. Nevertheless, with the continuous application of load, the material got to its break point. At the breaking point, the stress and the corresponding strain was recorded including the gauge length (i.e., after the fracture). During the testing, the mechanical properties such as; yield stress, tensile stress, fracture stress, elastic limit stress, ductility, young modulus, and elastic stain energy were examined.

Fig. 2 Annealed Samples before undergoing Tensile Test.

2.3 Yield Stress

The yield stress of the material is usually the point where there is appreciable elongation or yielding of the material without any corresponding increase in load. Although, it is very few materials that show yield point or stress but that did not take away the great importance because it occurs in mild steel which is an important engineering material. The yield stress of the material is commonly used as a measure of the strength of a material.

2.4 Proportional Limit Stress

The proportional limit stress of the material is the point at which the stress of the material is proportional to strain. It is from proportional manner of material that hooks law came to be.

2.5 Impact Test

The steel sample was cut to the required length of 40mm x10mm x 10mm using a grinding machine. The charpy impact testing machine was used to determine the impact strength of the samples. Before the testing was carried out, the samples were notched and measured using a hacksaw and vernier calipers. The samples were placed on the support at the base of the charpy impact testing machine, and it was align properly to ensure that the striker point mark align with the notched portion of the samples. After this step, the pendulum was released which gave a rupture, and the values on the dial gauge was recorded.

3. Results and Discussion

Figure 3 shows the samples after annealing heat treatments was carried out on them and subjection to tensile testing. While Table 1 shows the load and extension values gotten from the tensile test experiment. Table 2 shows the gauge length, yield load, maximum load, fracture load, yield stress, tensile stress and percentage elongation of each sample. Table 3 present the yield load and maximum load at various temperatures. Table 4 shows the yield stress, tensile stress and fracture load at various temperatures. Table 5 shows the impact test. From the analysis of the experimental result, it was revealed that the various alloying elements of steel have different effects on mechanical properties on metal.

The various properties of the alloying elements determine to a great extent their application with regard to the treatment to which the metal was subjected. Annealing heat treatment has huge effect on the mechanical properties of the roll steel as shown in Table 1-Table 5.

Fig. 3 Annealed Samples after undergoing Tensile Test

Table 1 Load Extension Readings for each sample

Sample	Load (KN)	Extension (mm)
	5	0.041
	10	0.045
	15	0.053
	20	0.837
A 650°C	25	1.722
	30	3.934
	5	0.020
	10	0.040
	15	0.085
B 700°C	20	1.605
	25	1.823
	27	2.992
	5	0.057
	10	0.071
	15	0.221
C 850°C	20	1.432
	25	2.992

	5	0.012
	10	0.036
	15	0.061
	20	0.663
D Control	25	1.204
	30	2.091
	34	2.632

Table 2 Tensile test result of ribbed bar of 30mm

SAMPLE	Dimension (mm)		Cross-sectional area (A_o)	Gauge length (mm)		Yield load (KN)	Max. load (KN)	Fracture load (KN)	Yield Stress N/mm^2	Tensile stress N/mm^2	% Elongation
	D_o	D_f		L_o	L_i						
A	10	6	78.54	50	52.6	15	30	25	4.86	381.97	5.0
B	10	5	78.54	50	54	20	27	20	4.38	343.77	8.0
C	10	5.4	78.54	50	59	15	25	20	4.053	318.31	18
D	10	7	78.54	50	51.6	20	24	30	5.512	432.90	3.2

Table 3 Yield and Max Load at Various Temperatures

Sample at various temp	Yield load	Max Load	Fracture Load
A 650^{0}C	15	30	25
B 750^{0}C	20	27	20
C 850^{0}C	15	25	20
D Control	20	34	30

Table 4 Yield Stress, Tensile Stress and Fracture at Various Temperatures

Sample at various temp	Yield stress (N/mm²)	Tensile stress (N/mm²)	Fracture load (KN)
A 650^{0}C	4.86	381.97	25
B 750^{0}C	4.38	343.77	20
C 850^{0}C	4.053	318.31	20
D Control	5.512	432.90	30

Table-5 Charpy Impact Test Result

Sample	Dimension (mm)		Area	Energy absorbed	Impact strength (J/mm^2)
	L	B			
A	55	2	110	50	0.45
B	55	2	110	50	0.454

C	55	2	110	49	0.445
D	55	2	110	44	0.4

From the results of the tensile test, it is reveal that samples B and C get to their fracture point much faster than sample A and D. This goes to show that there is decrease in ductility of both samples B and C as expected. This on the other hand confirms that samples A and D have more strength than samples B and C. Both the yield and tensile stresses for samples A and D were higher than their corresponding values for samples B and C. The results equally revealed that annealing has a considerable influence on the stress-strain relationship and properties of practically every engineering material. It equally affects the material compression strength. Besides, the ultimate strength, yield strength and stiffness decrease appreciably with increasing temperature, while percentage elongation (ductility) and malleability increases as the temperature rises. However, the reverse is generally true as the temperature is lowered. Figure 5 to Figure 8 show the plot of load against extension. The plot revealed that the annealing has effect on the extension of the material. It was observed that as the annealing temperature increases, minimum load is required to extend the material. This simply showed that annealing improve the ductility of the material. The rolled steel with the highest annealing temperature of 850^0C required the minimum applied load that causes an extension of 8cm.

Fig. 4 Charpy Impact Test Samples after Fracture

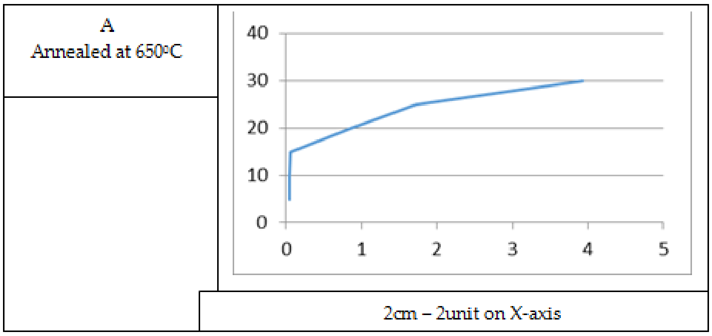

Fig. 5 Plot of Load against Extension for Sample A

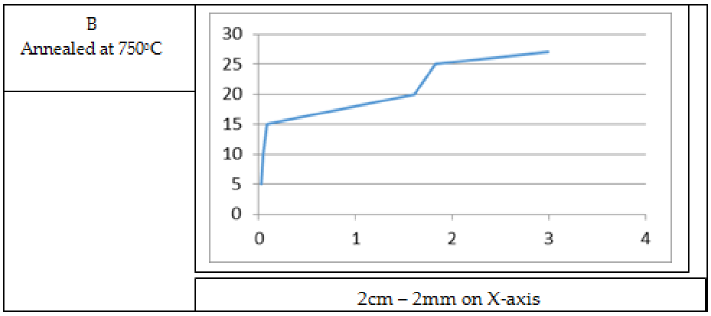

Fig. 6 Plot of Load against Extension for Sample B

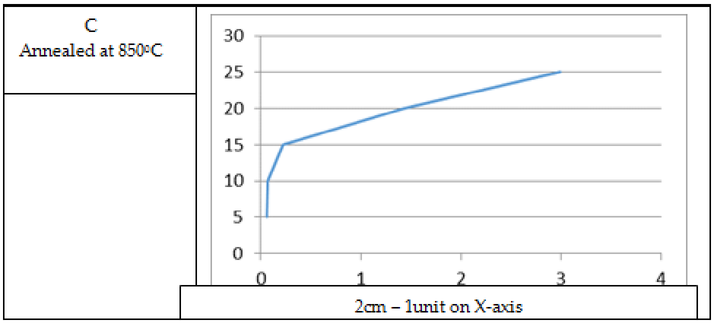

Fig. 7 Plot of Load against Extension for Sample C

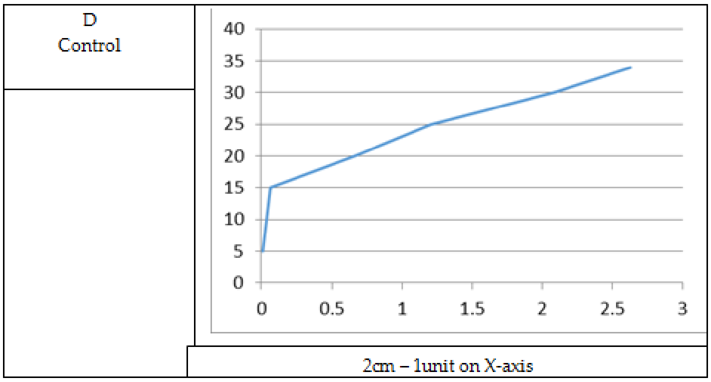

Fig. 7 Plot of Load against Extension for Sample D

Figures 9 to Figure 12 show the microstructure of the various stages of annealing heat treatment carried out on the specimens. The various stages showed the microstructure of the cold-work crystal at the physical stage. At this stage, the metal is in considerable mechanical stress resulting from internally balanced elastic strain. This elastic strain added to the jamming of the dislocation which occurred during cold information. Moreover, at the stress relief stage, there is a visible alternation in the distorted shape of the cold-work crystal. Stage B shows an observable alteration, where new crystals begin to grow from nuclei produced in the deformed crystal. Stage C shows the small crystals formed. At stage B, it has gradually grown to bigger crystal by absorbing each other in a cannibal-fashion; hence the structure is relatively coarse grained. In order words:

i. Between 0^0C – 650^0C, there is a great transformation as the structure or micrograph revealed different picture. Again there is increase in grain size, the normal has fine grain size but at 650^0C the grain is coarse (compare control and 650^0C).

ii. Between 650^0C –750^0C, there was no serious transformation although the carbon has started precipitating as seen in Figure 10 (the dark part) ("patches"). But the structure is still revealing ferrite and pearlite. The dark part is the pearlite containing mounting carbon while the white part is ferrite containing mainly ferrous part. The grain size is relatively the same between 650^0C – 750^0C.

iii. Between 750^0C – 850^0C, there is a serious transformation. There the grain boundaries could no longer be seen clearly. Besides, the ferrite has precipitated with the pearlite thus forming grey color instead of clear white and black. The grain size is the largest. The implication is that there longer or coarse grain size as the materials got soften.

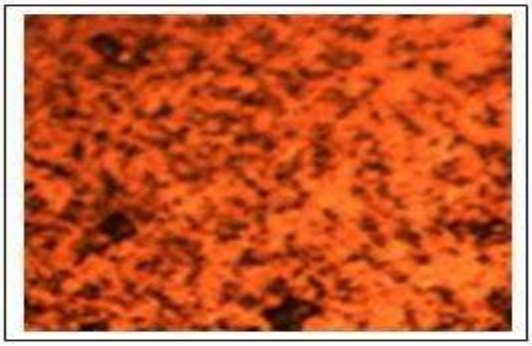

Fig. 9 Photomicrograph of sample A, annealed at 650^0C

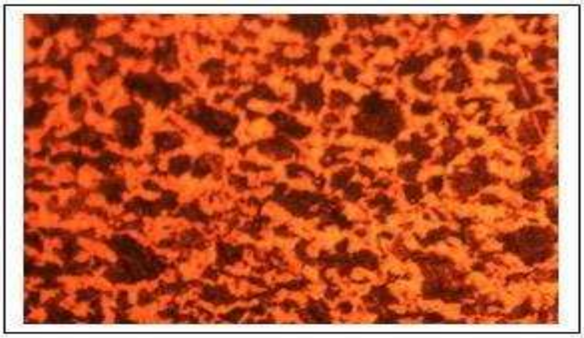

Fig. 10 Photomicrograph of sample B, annealed at 750^0C

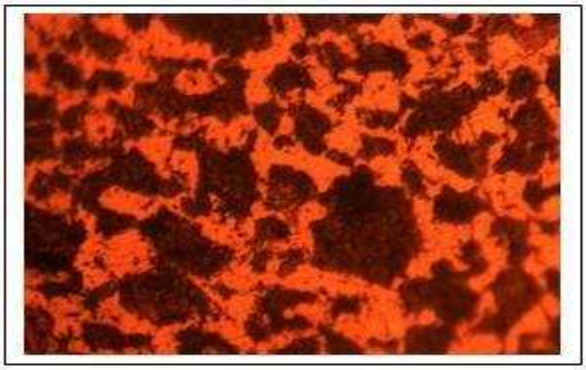

Fig. 11 Photomicrograph of sample C, annealed at 850^0C

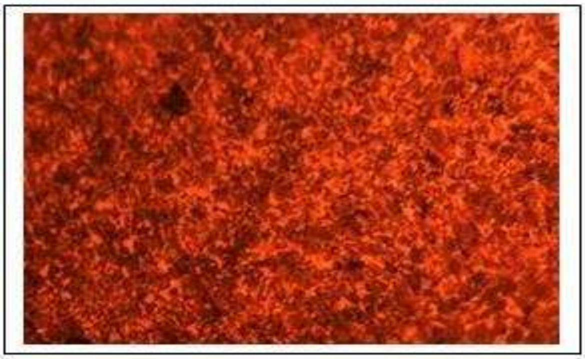

Fig. 12 Photomicrograph of sample D, control specimen

4 CONCLUSION

From the analysis of the experimental result, it can be deduce that various alloying elements of steel have different effects on its mechanical properties. The various properties installed by the alloying elements determine to a great extent their application. Treatment to which the metal was subjected affect the properties and hence application. Thus each required application determines the heat treatment carried out on the metal. Also, steel alloys generally have higher strength than the pure metal in the same condition and relatively inexpensive alloy when compare with non-ferrous alloys generally. Hence steel is by far the most important engineering alloy. Furthermore, annealing heat treatment has a considerable influence on the load-extension relationship and properties of practically every engineering material. It even affects it compression strength in the case of an engineering metal. The ultimate strength, yield strength and stiffness decreases appreciably with increasing temperature, while percentage elongation (ductility) and malleability increases as the temperature rises. The reverse is generally true as the temperature is lowered.

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