Effect of Process Annealing Temperature on Some Tensile Properties and Microstructure of Cold Rolled 1010 Steel.

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Abstract

This paper aims to investigate the effect of temperature of process annealing heat treatment on some tensile properties and microstructure of cold-rolled 1010 steel. The cold-rolled sheet was cut into the standard tensile test specimens and then the samples were annealed at 300, 400, 500, 550, 600, and 650ºC. Tensile and microscopic tests were conducted on the samples. Process annealing temperatures had a significant effect on properties and microstructure. Yield and Ultimate tensile strengths decreased massively from 638 and 662 MPa of the cold rolled steel to 169 and 309 MPa respectively of the treated samples at 650ºC. On the other hand, percent elongation improved noticeably from 2 to 35 percent. The microstructure showed a formation of a new set of free-strain grains, that is, the recrystallization temperature, starting at 600ºC and finishing at 650ºC. This range was of the transition from brittle to ductile fracture. The dominant microstructure was ferrite and pearlite, with elongated grains before 600ºC and recrystallized grains at 600ºC and above.

I. INTRODUCTION

Cold rolling is a work hardening process used to change the shape and structure of metals and alloys without the use of heat. Cold rolling has a great effect on microstructure and hence properties of metals and alloys. This effect takes place because recrystallization does not occur and the dislocation density in a metal increases. This results in a strengthening of the metal, making an increase in strength properties and a decrease in plastic properties. Cold rolling as a type of cold working increases the dislocation density by some orders of magnitude. Dislocations are crystal defects associated with internal stresses. The increase in dislocation density causes the accumulation of internal stresses. As the plastic deformation increases, the strengthening of the material is enhanced. This is characterized by an increase in tensile and yield strengths and a decrease in elongation. Moreover, the microstructure also changes because of the extension of grains in the direction of rolling. As a result, a specific heat treatment operation might be conducted to alleviate all these changes, and it is called process annealing[1,2].

Process annealing is an annealing process at temperatures above the recrystallization temperature of the cold-worked material, without phase transformation. It aims at developing properties and changing the microstructure existing after a cold-forming process. Process annealing has three stages, which are recovery, recrystallization, and grain growth.

In the recovery stage of annealing, which occurs at lower temperatures, the physical and mechanical properties tend to recover. These properties could be altered slightly and gradually as the temperature increases without an apparent change in the microstructure.

Recovery, in this case, is probably a matter of annihilating excess dislocations. Such annihilation can occur by the coming together of dislocation segments of opposite signs. That is, negative edges with positive edges and left-hand screws with right-hand screws. In this process, dislocation slip and climb mechanisms are involved. Dislocations become mobile at a higher temperature, eliminate and rearrange to give polygonization. At this stage of annealing, the resistivity is almost completely recovered before the state of recrystallization. On the other hand, the change in strength properties occurs slightly and gradually. Higher temperatures are needed, and that is called recrystallization of the matrix[1,3,4].

At a higher temperature, new, strain-free grains nucleate and grow inside the old distorted grains. This takes place in high-energy areas such as grain boundaries and high dislocation density.

These new grains grow to replace the deformed grains produced by the strain hardening. The driving force for recrystallization comes from the stored energy of cold work. When polygonization is completed, the stored energy can be assumed to be confined to the dislocations in polygon walls. The elimination of the sub-boundaries is a basic part of the recrystallization process[1,2]. Factors influencing recrystallization temperature are chemical composition, microstructure, alloying elements, purity, cold reduction, and annealing patterns[5]. Once the recrystallization is complete, the third step of the process annealing begins.

In a completely recrystallized metal, the driving force for grains to grow depends on the surface energy. As the grains grow in size and their numbers decrease, the grain boundary area diminishes and the total surface energy is lowered accordingly. In this step, mechanical properties will not change as much as all the stored energy has already been released[1,3].

Materials respond to fracture differently depending on their microstructure and properties. The two most famous types of fracture are ductile and brittle. Classification is based on the ability of a material to experience plastic deformation. Ductile metals typically exhibit substantial plastic deformation with high energy absorption before fracture. However, in a brittle fracture, there is almost no energy absorption and therefore no plastic deformation. The fracture surface of the ductile fracture appears dull and fibrous, showing a cup-and-cone. On the other hand, brittle fracture is usually flat and shiny. Moreover, the two parts of a brittle fracture can be put back together easily, whereas it is not the case in a ductile fracture[6,7]. As discussed earlier, cold-rolled materials experience brittle fractures while fully recrystallized materials experience ductile fractures.

This experiment aimed to investigate the changes in microstructure and some tensile properties of cold-rolled low carbon steel (1010 Steel) due to the effect of process annealing temperature.

II. EXPERIMENTAL PROCEDURE

A. Material

Seven specimens of cold-rolled 50% low carbon 1010 steel were cut in a special mold by impact shear. They were collected from the stock material of a 1.5 mm thickness into the standard shape of the tensile test specimens.

The chemical composition of the most important alloying elements of this steel is shown in Table 1.

TABLE 1. THE CHEMICAL COMPOSITION (wt%) OF STEEL

Fe	C	Mn	P	S
99.497	0.103	0.350	0.020	0.030

B. Heat Treatment

Six specimens were process annealed at 300, 400, 500, 550, 600, and 650ºC for 1 hour. Then the specimens were slowly cooled to room temperature in the furnace.

C. Tensile Test

The tensile test was carried out on the seven specimens, the cold rolled and the six heat treated, to determine the changes in mechanical properties. These properties are percent elongation, yield strength YS and ultimate tensile strength UTS. Moreover, the fracture shape could be observed.

D. Microscopic examination

All the specimens were examined microscopically. Specimens were cut, mounted, ground, polished, and etched to be examined with the optical microscope.

III. RESULTS AND DISCUSSION

The tensile properties obtained from the samples are shown in Table 2. These properties are plotted in Fig. 1 and 2.

TABLE 2. TENSILE PROPERTIES OF SAMPLES

Sample	% Elongation	Yield Strength *YS, MPa*	Ultimate Tensile Strength *UTS, MPa*
Cold Rolled	2	638	662
Heat Treated at 300ºC	4	616	651
Heat Treated at 400ºC	6	588	637
Heat Treated at 500ºC	10	518	586
Heat Treated at 550ºC	18	428	519
Heat Treated at 600ºC	34	174	311
Heat Treated at 650ºC	35	169	309

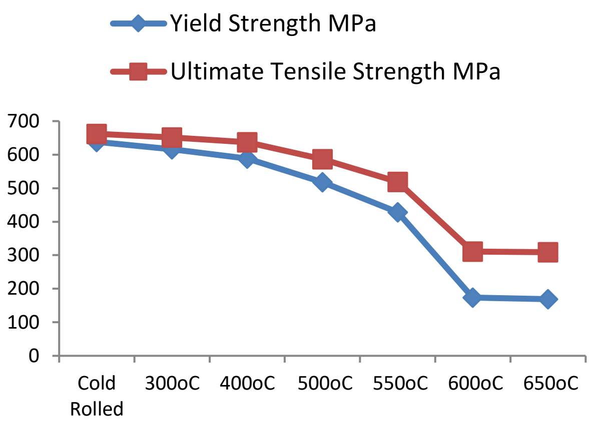

Figure 1. Values of Yield and Ultimate Tensile Strengths of tested specimens.

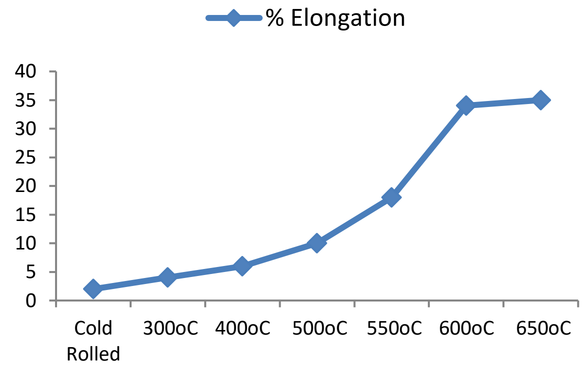

Figure 2. Values of Percent Elongation of Tested Specimens.

A. Cold-rolled sample

When a metal is plastically deformed at a low temperature, atoms cannot rearrange themselves. In the case of cold rolling, dislocations move and additional dislocations are generated. The more dislocations within a material, the more they will interact and become pinned or tangled. This will result in a decrease in the mobility of the dislocations and a strengthening of the material. However, increasing the strength by cold-working will also result in a reduction in ductility. The tensile results of the cold-rolled sample reflect the strengthening. Yield strength is 638 MPa, Ultimate tensile strength is 662 MPa and, the elongation is 2% for this cold-rolled sample. A similar trend in high yield and ultimate tensile strengths and low ductility due to cold working was investigated[8, 9]. Moreover, higher levels of strength can be achieved if desired[9]. The small gap between yield strength and ultimate tensile strength indicates brittle behavior as well as very little % elongation. That was obvious from the fracture of the sample, which took place in the gauge length, as shown in Fig. 3a. The fracture is flat and the two parts could be put back together; there is no cup and cone appearance.

a **b** **c** **d** **e** **f** **g**

Figure 3. The specimens; (a): Cold Rolled, (b): Treated at 300ºC, (c): Treated at 400ºC, (d): Treated at 500ºC, (e): Treated at 550ºC, (f): Treated at 600ºC, (g): Treated at 650ºC.

The microstructure of the cold-rolled sample consists of ferrite and pearlite as shown in Fig. 4. Cold rolling is typically performed at room temperature or at temperatures significantly lower than the recrystallization temperature. As a result, the grains were elongated and extended in the direction of rolling.

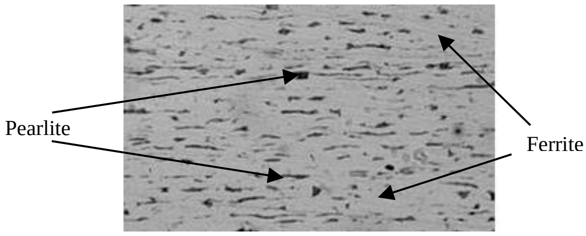

Figure 4. Optical micrograph showing the microstructure of the cold-rolled sample (100x).

B. Heat Treated sample at 300ºC

The mixture of phases stays the same, ferrite and pearlite, during all temperatures, as phase transformation is not involved. When strain-hardened materials are exposed to elevated temperatures, their strength properties decline and plastic properties develop[10-12]. When a strain-hardened material is kept at an elevated temperature, an increase in atomic diffusion occurs. This results in relieving some of the internal strain energy.

Atoms can move around when they have enough energy to break their bonds. As the temperature increases, atoms in severely strained regions can move to unstrained positions. Therefore, atoms have sufficient energy to move and recover normal positions in the lattice structure. This is known as the recovery phase, and it results in an adjustment of strain on a microscopic scale. Dislocation density reduction and movement of dislocations to lower-energy positions release internal residual stresses. The tangles of dislocations condense into sharp two-dimensional boundaries, and the dislocation density within these areas decreases.

This specimen was annealed at 300ºC and its tensile properties changed only slightly. YS decreased from 638 to 616 MPa and, similarly, UTS declined from 662 to 651 MPa. On the other hand, % elongation improved from 2 to 4%. This temperature affected the specimen slightly, as reflected by the change in properties and as reflected by the fracture surface, which was still considered to be brittle, as shown in Fig. 3b.

C. Heat Treated sample at 400ºC

This specimen was annealed at 400ºC and the variation of properties was higher than at the previous temperature. YS decreased from 638 to 588 MPa and, similarly, UTS declined from 662 to 637 MPa. On the other hand, % elongation improved from 2 to 6%. The atoms have experienced a higher temperature, allowing them to move to more stable positions. Moreover, the internal energy due to dislocation density is lowered. However, the tendency towards brittle fracture is still dominant, as shown in Fig. 3c.

D. Heat Treated sample at 500ºC

The gap between YS and UTS became clearer and higher than the previous temperatures, as shown in Fig. 1. YS decreased from 638 to 518 MPa and, similarly, UTS declined from 662 to 586 MPa. On the other hand, % elongation improved from 2 to 10%. However, there was still no appearance of ductile fracture as shown in Fig. 3d even though more energy was released at this temperature.

E. Heat Treated sample at 550ºC

At 550ºC, the strengthening properties declined sharply and plastic properties developed massively. Yield strength decreased from 638 to 428 MPa, whereas ultimate tensile strength declined from 662 to 519 MPa. On the other hand, % elongation improved from 2 to 18%. This improvement in % elongation was clear in Fig. 3e as compared to the cold-rolled sample. On the other hand, and irrespective of this change of properties, the fracture of the heat-treated sample at 550ºC did not show the features of ductile fracture. Another piece of evidence showing that it is still the recovery temperature is the microstructure of this sample, as shown in Fig. 5.

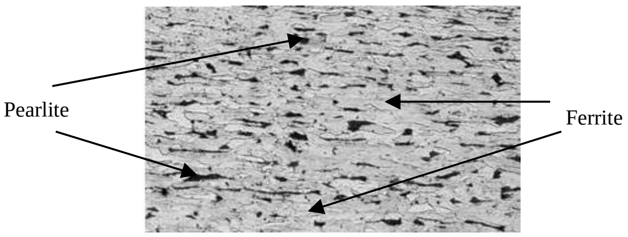

Figure 5. Optical micrograph showing the microstructure of the heat-treated sample at 550ºC (100x).

No new grains appear in Fig. 5 as the grains are still elongated. As a result, the recrystallization has not occurred yet. Recovery is still dominant at 550ºC in several low-carbon steel alloys[13, 14].

What happened in recovery, which was the case of all previously treated samples, was mainly due to polygonization. Polygonization involves dislocation glide and climb. Because polygonization involves dislocation climb, relatively high temperatures are required for rapid polygonization. In deformed polycrystalline metals, high-temperature recovery is considered to be essentially a matter of polygonization and annihilation of dislocations. As a result, the release of internal energy at 550ºC was much more pronounced than at 300ºC due to polygonization. At lower temperatures, the recovery process is primarily a matter of reducing the number of point defects to their equilibrium value. The most important point defect is a vacancy that may have finite mobility even at relatively low temperatures[15].

F. Heat Treated sample at 600ºC

Fig. 3f can explain the whole behavior of the sample. This sample has undergone a very high % elongation compared with the previous samples, and the fracture surface is considered to be ductile. This ductile fracture was clear due to the appearance of the neck, the cup, and the cone feature. Moreover, due to the formation of the neck, the two parts of the sample cannot be put back together easily. Fig. 6 proves the ductile behavior, as the deformed grains were replaced by new strain-free grains. A critical amount of deformation is essential for the recrystallization to occur during heating. The 50 % deformation was suitable for the nucleation to occur. It took place in regions of severe localized deformation, such as areas of grain boundary or dislocation density. It is possible to form a small, strain-free volume that can grow out and consume the deformed matrix around it[16, 17]. This was the sign of the release of the stored energy due to cold rolling.

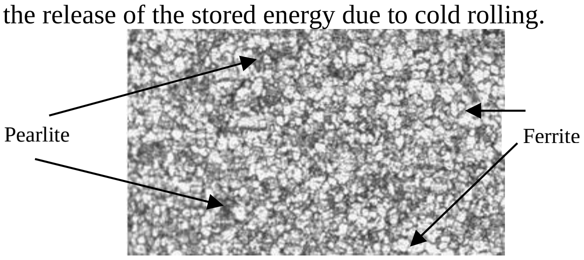

Figure 6.Optical micrograph showing the microstructure of the heat-treated sample at 600ºC (100x).

The change in tensile properties was huge due to the release of stored energy. The elongation reached 34 %, the yield strength is 174 MPa and the ultimate tensile strength is 311 MPa. These values mean that the strain energy due to cold working was released. Once the recrystallization occurs, the mechanical properties and microstructure change drastically[18]. Recrystallization starts at an annealing temperature of around 600°C for several steel alloys under different conditions[13,19-22]. However, the fully recrystallized microstructure might need a slightly higher temperature or time.

G. Heat Treated sample at 650ºC

The mechanical properties at 650°C have only changed slightly compared with 600°C because the stored energy has already been released. Elongation changed from 34 to 35%, Yield strength from 174 to 169 MPa, and ultimate tensile strength from 311 to 309 MPa. Moreover, the features of ductile behavior are clear, as shown in Fig. 3g, for the reasons discussed in the previous section. The difference between these two temperatures is demonstrated in Fig. 7. It shows the end of the recrystallization process because, after nucleation, the nuclei grow up to a certain size before grain growth.

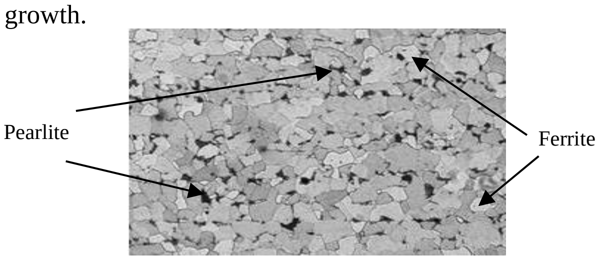

Figure 7. Optical micrograph showing the microstructure of the heat-treated sample at 650ºC (100x).

This alloy, 1010 steel, has some similarities and differences with other alloys when subjected to annealing. When high manganese austenitic steel is annealed at 700ºC, the % elongation was close to the 650ºC but the YS and UTS were much higher[23].

When 316L was annealed, the strength of the specimens decreased with increasing annealing temperature. Much better ductility can be achieved with a similar annealing temperature[24].

Another alloy used was cold-rolled Low-Carbon Steel with Ultrafine Grains and a martensitic starting structure. When it was annealed at 550ºC for 30 min, the result was a mixed microstructure. It is composed of ultrafine equiaxed ferrite grains and uniformly distributed nano-carbides. This microstructure had a good combination of 867 MPa of tensile strength and 16.7% of elongation[25]. The tensile strength was much higher than the experimental alloy, but the elongation was close.

A slightly higher temperature is required for recrystallization to occur in Dual-Phase Ultrahigh-strength TWIP Steel than in the experimental alloy[26].
As the annealing temperature increased, the strength decreased while the elongation increased for cold-rolled Fe–13Cr–4Al alloys[27].

IV. CONCLUSIONS

1. Annealing to temperatures up to 550ºC did not lead to remarkable softening, while heating to higher temperatures resulted in almost complete softening.
2. The recrystallization starts at 600°C and finishes at 650°C for this 1010 steel.
3. From the cold rolled to the crystallization state, the properties change massively. The alloy loses 464 MPa from Yield strength, and 351 MPa from Ultimate tensile strength while it gains 32% elongation.
4. Once the recrystallization starts, the yield and tensile properties become almost temperature-independent.
5. The brittle fracture appears before 600ºC and grains are elongated with ferrite and pearlite microstructure.
6. The ductile fracture starts to be noticeable at 600ºC and above and grains are recrystallized with ferrite and pearlite microstructure.

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