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ORIGINAL RESEARCH ARTICLE

MECHANICAL AND STRUCTURAL RESPONSES OF LOW CARBON STEEL TO COLD ROLLING AND STRESS RELIEF ANNEAL TREATMENTS

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ABSTRACT

This study investigated the effect of deformation by cold rolling and stress relief anneal on the mechanical and structural properties of low carbon steel. The as-received steel samples were cold rolled at 20% – 40 % degrees of deformation using Buhler rolling machine in Metallurgical and Materials engineering department University of Lagos, Nigeria. Additionally, some of the cold rolled samples were annealed at a temperature of 650° C and soaked for 1 hour in a muffle furnace. The results revealed that the ultimate tensile strength (UTS), percent elongation, hardness and impact strength of the cold rolled low carbon steel improved significantly after stress relief anneal due to the elimination of induced strain hardening caused by cold rolling. The micrographs show that cold rolled + stress relief anneal caused significant recrystallization of ferrite-austenite phase to refine martensite with reduction of dislocations. Therefore, the low carbon steel can be used effectively for structural purposes in machines and equipment.

1.0 Introduction

Plain Carbon Steels are widely used for many industrial applications and manufacturing on account of their low cost and ease of fabrication. In general, plain carbon steels are classified based on their carbon content, Steels with carbon content varying from 0.3% to 0.6% are classified as medium carbon, while those with carbon content less than 0.25% are termed low carbon. Those with high carbon content in the range 0.65-1.5% are classified as high carbon steels.

Low carbon steel has attracted a lot of research around the globe due to its numerous industrial applications. In industries, cold rolling is largely responsible for structural changes in engineering materials which often result in improved mechanical properties due to gradual extension of grains in the direction of the principal deformation stress with no recrystallization occurring. A Low Carbon Steel subjected to intercritical annealing at 850oC exhibited a dual phase microstructure consisting of ferrite martensite and presented excellent mechanical properties in term of hardness, strength and elongation (Phoumiphon et al., 2016). To further enhance the mechanical properties of engineering materials, heat treatment operation is carried out on low carbon steels to obtain desirable mechanical properties like hardness; toughness; ductility; strength. Low carbon steel is the most common form of steel as its price is relatively low while it provides material properties that are acceptable for many applications. LCS has a low carbon content (up to 0.3%) and is therefore neither extremely brittle nor ductile. It becomes malleable when heated, and so can be forged, rolled or machined into any shape.

Several studies have been conducted to examine the influence of cold rolling and heat treatment on the mechanical properties of engineering materials. The effect of soaking time on the mechanical properties of annealed cold drawn carbon steel has been conducted (Raji and Oluwole, 2012). Similarly, Rintaro et al. (2003) investigated the effect of the rolling reduction on the ultrafine grained structure and mechanical properties of plain low-carbon steel processed from martensite starting structure (Ueji et al., 2004). In addition, the effect of severe plastic deformation on the mechanical properties of chosen material was studied. It was found that the microstructure was highly refined resulting in formation of nanosized grains that enhanced the tensile and hardness of the material. Ayoola and Oyetunji (2014) studied the effect of deformation and annealing processing on the texture and mechanical properties of aluminium alloy AA1200. The study found that ultimate tensile strength and hardness depends on the degree of deformation (Ayoola and Oyetunji,2014). Furthermore, the influence of cold rolling and annealing on mechanical properties of steel QStE420 was investigated (Schindler et al., 2009). It was observed that combination of size of previous cold deformation and parameters of the following annealing, it was possible to influence mechanical properties of particular steel. Phoumiphon et al. (2016) examined the effect of cold rolling and intercritical annealing on the mechanical properties of plain low carbon steel. Many steel components failed in service due to residual stresses from previous processing and fabrication techniques such as forging, extrusion and rolling. Therefore, this study aimed to investigate the effect of cold rolled deformation and stress relief anneal on the mechanical and structural properties of low carbon steel with a view to solving failures caused by plastic deformations during materials processing.

2. Materials and Methods

2.1 Materials

The steel used in this study was procured from Finlab Scientific Store in Lagos Nigeria. The nominal chemical composition of the steel shown in Table 1 indicated that the steel is a commercial grade low carbon steel rod with a diameter of 16 mm.

Table 1: Chemical Composition of As-Procured Plain carbon Steel used (Finlab Scientific Store, Lagos. Nigeria)

Elements	Fe	C	Si	Mn	P	S	Cr	Ni
Weight (%)	98.940	0.225	0.170	0.540	0.017	0.008	0.074	0.026

2.2 Samples preparation

The as-procured low carbon steel rod was cut into 250 mm long samples and cold rolled at room temperature (28° C) in a Buhler two-high rolling machine 150 x 80A at Metallurgical and Materials Engineering Foundry Unit, University of Lagos, Akoka, Lagos Nigeria. Table 2 shows the deformation parameters used to produce samples in accordance with ASTM E8-8ST standard (Adeosun et al., 2011). The rolling was done by feeding the sample in the rolling machine, which is preset to allow for the required degree of deformation and number of passes. The deformed samples were heat treated in a muffle furnace at a temperature of 650 °C soaked for 1 hour and later cooled to room temperature in air.

Table 2: The Deformation parameters and their values (Adeosun et.al, 2011)

Deformation parameters	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Sample diameter (mm)	12.80	12.0	11.20	10.40	9.60
Degree of deformation (%)	20	25	30	35	40
Reduction in diameter (mm)	3.20	4.00	4.80	5.60	6.40
Number of passes	1	2	4	8	16

2.3 Mechanical Testing

2.3.1 Tensile Test

The tensile test was conducted on Instron Universal Testing Machine model (USA). The tensile test pieces were prepared from the rolled and heat treated samples to ASTM E-8 standard (Ayoola et al., 2012, Tewary et al., 2015). Figure 1 shows the standard dimensions of the specimen used in this study. From the tensile tests carried out, tensile strength and percentage elongations were determined.

Figure 1: Cylindrical Tensile Test Piece

2.3.2 Flexural Test

The flexural test was done using M500 tensometer (USA) with a load of 25KN on samples. Specimens of 120 mm long by 50 mm wide were cut and loaded in three point flexural with a recommended span of 100 mm and also with a test speed of 40 mm/min.

2.3.3 Hardness Test

To evaluate the hardness of the material the Rockwell hardness test was carried out according to ASTM E-18 specification (Paul et al., 2007).

2.3.4 Impact Test

Impact test was carried out on the samples using the Avery- Denison Universal Impact –Testing Machine. (USA) The energy absorbed by the machined sample was measured and recorded when the machine pendulum was released from the maximum position corresponding to charpy test, striking the test piece with a load of 300 J (Paul et al., 2007). The same procedures were repeated on other samples

2.3.5 Microstructural Analysis

Microstructural examination of samples was conducted using a metallurgical optical microscope in line with Gladkousky et al. (2016). The specimens for the optical microscopy were ground using a series of emery papers of grit sizes ranging from 500 – 1500 µm while fine polishing was done afterwards. The specimens were etched with 2% Nital solution for 5 seconds before observation in the optical microscope.

3. Results and Discussion

This study investigated the effect of deformation by cold rolling and stress relief anneal on the mechanical and microstructural properties of low carbon steel. Table 3 indicates the Mechanical properties of the control sample while Figure 2 shows the mechanical properties of the samples that were cold rolled with and without stress relief anneal at various degree of deformation. The Ultimate Tensile Strength of the cold rolled samples without stress relief anneal increased with increasing degree of deformation and significantly higher than that of control and stress relief anneal samples. Figure 2 also reveals that increase degree of deformation has no significant effect on the UTS for the cold rolled + stress relieved samples. This implies that stress relief anneal at 650° C for 1 hour is sufficiently high enough to eliminate the strain hardening and induced residual stresses completely. This is because the recovery process, that is, stress relief anneal significantly allowed redefined and rearranged of large numbers of dislocations within grains resulted in reduce or complete elimination of residual stresses. The UTS of rolled + stress relief anneal samples were approximately 2.5 higher than the cold rolled samples. This may be linked to the stress relief anneal temperature of 650° C investigated. At higher annealing temperatures, both recovery and recrystallization occur rapidly and resulted in grain growth which reduces the UTS of the samples (Ueji et al., 2004).

Table 3: Mechanical properties of the As Received Low Carbon Steel.

UTS (MPa)	Impact Energy (J)	% Elongation	Hardness
505.56	206	15.03	4.40

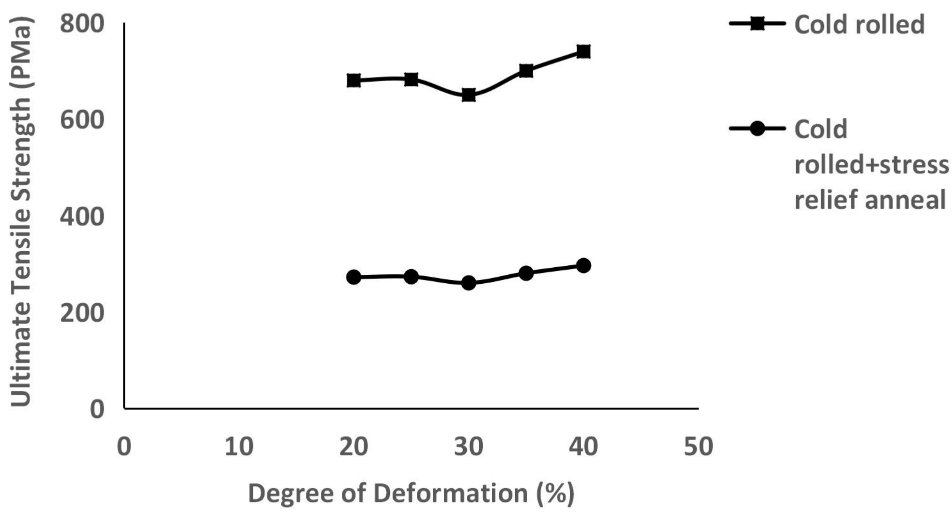

Figure 2: Variation of Ultimate Tensile Strength with Annealing and Degree of Deformation

Figure 3 shows the dependence of percent elongation on the degree of deformation. While the percent elongation increased with the degree of deformation for the cold rolled samples the rolled + stress relief anneal samples show some form of recovery. The percent elongation dropped at all levels of deformation after stress relief of the samples. Figure 3 shows that 18% and 75 % reduction in elongation were obtained at 20% and 40 % degree of deformation, respectively. The elongation recovers when the samples are annealed at temperatures higher than 550° C (Ueji et al., 2004). A gradual increase in the elongation was noticed beyond 30 % degree of deformation for the cold rolled + stress relief anneal. Elongation of materials is a measure of its ductility. Stress relief anneal improved the ductility of the low carbon steel investigated due to the elimination of residual stresses induced. Between 20 and 30 % degree of deformation, percent elongation of cold rolled + stress relief anneal samples was observed to be closer to the original ductile of the as-received sample of 15 %.

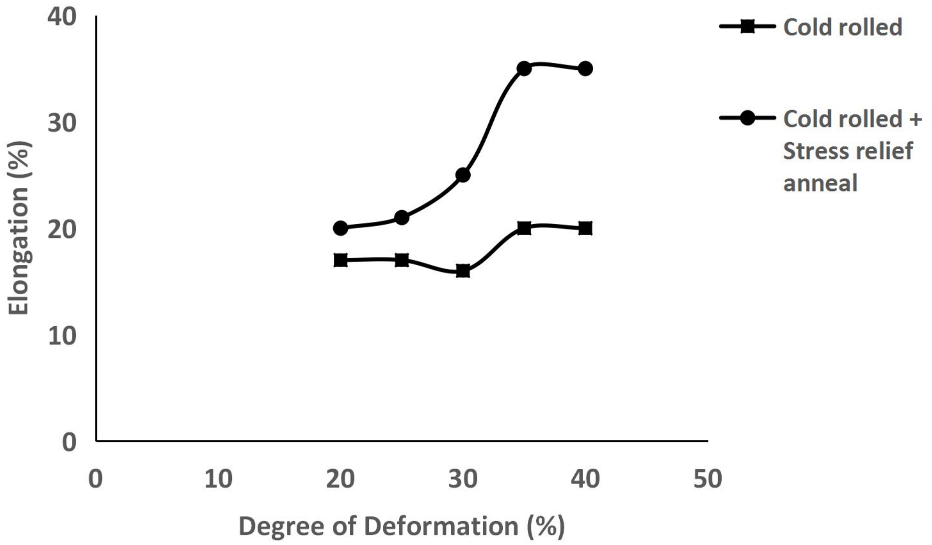

Figure 3: Variation of Elongation with Annealing and Degree of Deformation

Figure 4 shows the response of flexural strength to the degree of deformation. Flexural strength decreases with increasing degree of deformation. The maximum flexural strength obtained for the rolled sample and rolled + stress relief anneal sample are 1900 MPa and 840 MPa respectively. Similarly, the least flexural strength obtained for the rolled sample and rolled + stress relief anneal sample are 1260 MPa and 360 MPa respectively.

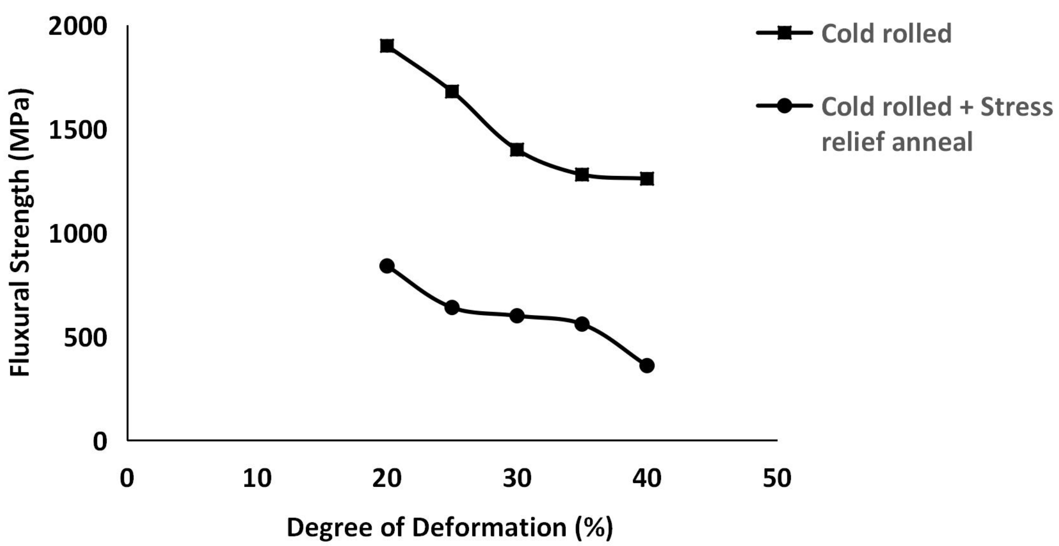

Figure 4: Variation of Flexural Strength with Annealing and Degree of Deformation

Figure 5 shows the effect of stress relieved annealing and degree of deformation on the sample hardness. As expected, the hardness value of the samples is a function of the processes the

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material is undergone. The rolled samples without stress relief anneal exshibited higher hardness compared to rolled + stress relief anneal samples. However, the slopes of the plots are similar. It can also be seeen that the hardness increased with increasing degree of deformation and dependent of stress relief anneal. Cold rolled samples without stress relief anneal introduced commpressive residual stress, which is beneficial for parts that are subject to cyclical loads because it helps to prevent the initiation and propagation of cracks. However, with the annealed samples, compressive residual stress have been largely eliminated and tensile residual stress seems to have been introduced, which translated to drasstical reduction in hardness. The hardness of the stress relief anneal samples is higher than that of the control sample.

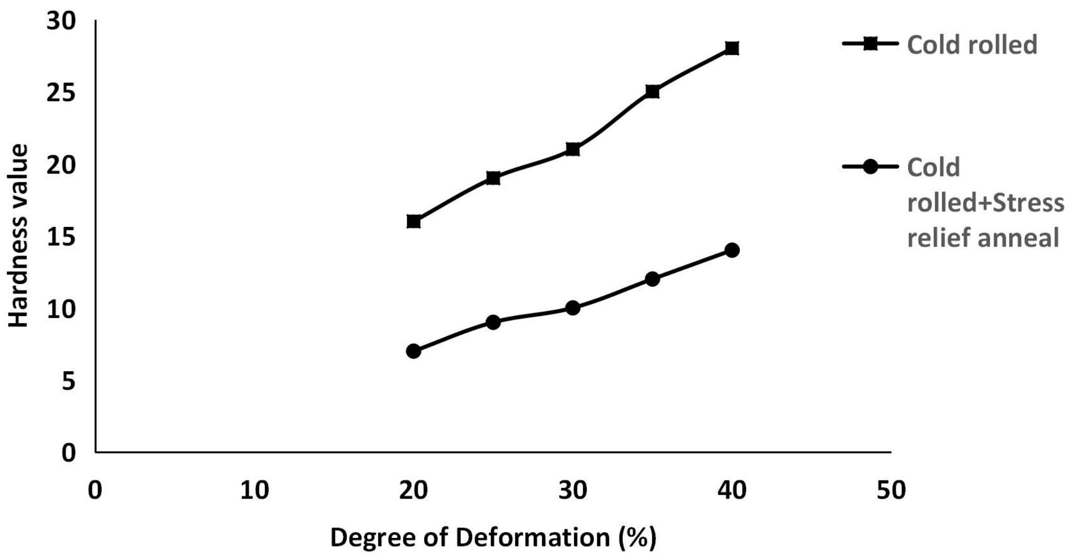

Figure 5: Variation of Hardness with Annealing and Degree of Deformation

The absorbed impact energy by the samples cold rolled with and without stress relief anneal is shown in Figure 6. The trend of the two curves is similar. The linear regression lines fitted show that the impact strength is not enhanced by increasing the degree of deformation irrespective of treatment undergone. However, the influence of stress relief anneal can be seen. The impact energy of 220 J and 135 J were recorded for stress relieved and cold rolled samples, respectively.

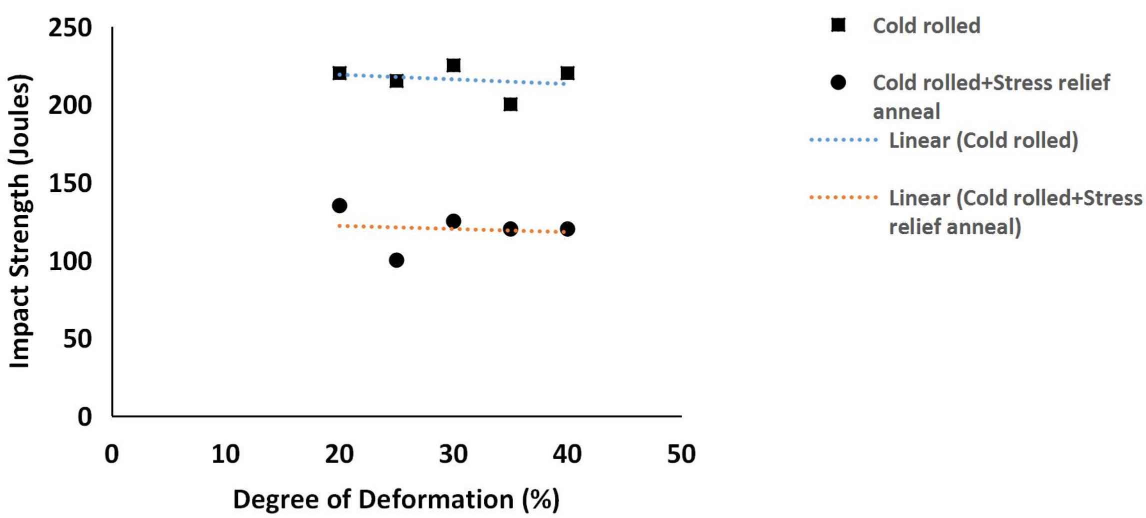

Figure 6: Variation of Impact Strength with Annealing and Degree of Deformation

Figure 7 shows the micrograph of the as-received low carbon steel. Figures 8, 9, 10, 11 and 12 show the micrographs of the samples deformed at 20, 25, 30, 35 and 40 %, respectively. Interestingly, the micrographs are predominantly ferrite-austenite and martensite phases. It is noteworthy that large grains of the martensite phase of the as-received sample are regular in shape and well visible within the matrix of ferrite-austenite phase, as shown in Figure 7. The volume fraction of the martensite and ferrite-austenite phases are well distributed. Figures 8a, 9a, 10a, 11a and 12a are the micrographs of cold rolled samples while Figures 8b, 9b, 10b, 11b and 12b are the micrographs of cold rolled + stress relief anneal samples at the same degree of deformation, in that order. The micrographs of the cold rolled samples contain deformed grains of smaller sizes which contain a very large number of dislocation than the cold rolled + stress relief anneal samples. The presence of these dislocations are largely responsible for the enhanced mechanical properties attained in the stress relieved samples. Expectedly, stress relief anneal above 0.4*Tm (Tm, melting temperature of low carbon steel) caused recrysallisation of low carbon steel, elimination of the residual stresses and most dislocations, which subsequently reduce ultimate tensile strength with high ductility (Ueji et al., 2004). Application of stress relief anneal to the cold rolled samples caused major coalesence of the smaller martensite grains to larger grains of irregular shapes and increased the volume fraction due to recrystallisation. Phoumiphon et al., 2016 reported that the ferrite-austenite dual phase region by referring to the lever rule, the volume fraction of austenite increases depends on annealing temperature, then will transform to martensite. Also, Gladkousky et al. (2016) revealed the possibility of the formation of an ultrfine grained structure in a steel layer during rolling. The stress relief anneal temperature is significantly high enough for recrytallisation of low carbon steel (Knupfer and Moore, 2010; Phoumiphon et al., 2016). Figure 12b shows that sample cold rolled at 40 % deformation and stress relief anneal exhibited highest presence of mentensite phase, which transilated to the highest hardness and UTS. The higher hardness and UTS recorded for the Figure 12a over Figure 12b was due to the large volume of dislocation present. The findings from this work is in agreement with most of the earlier studies cited and the results further revealed the adaptability and hence the effective utilisation of the low carbon steel for structural applications when rolled and stress relieved optimally.

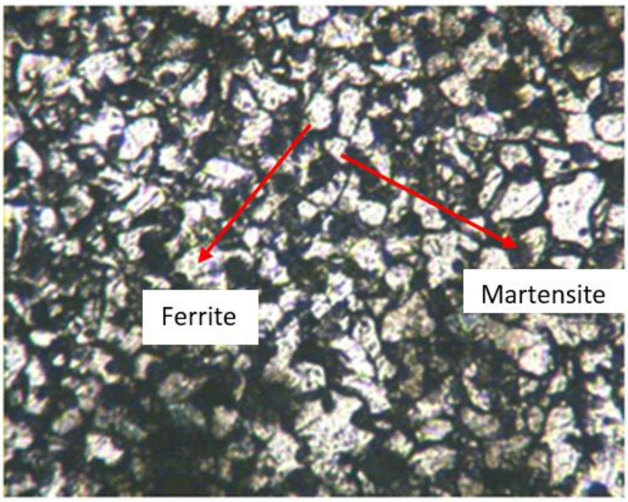

Figure 7: Micrograph of the control sample in as-received condition

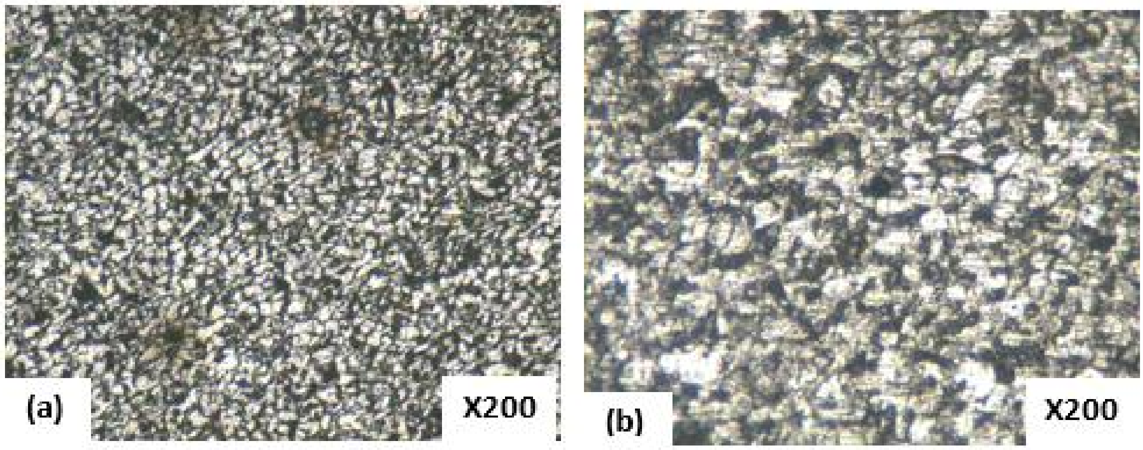

Figure 8: Micrograph of samples at 20% deformation (a) rolled and (b) rolled + stress-relief anneal

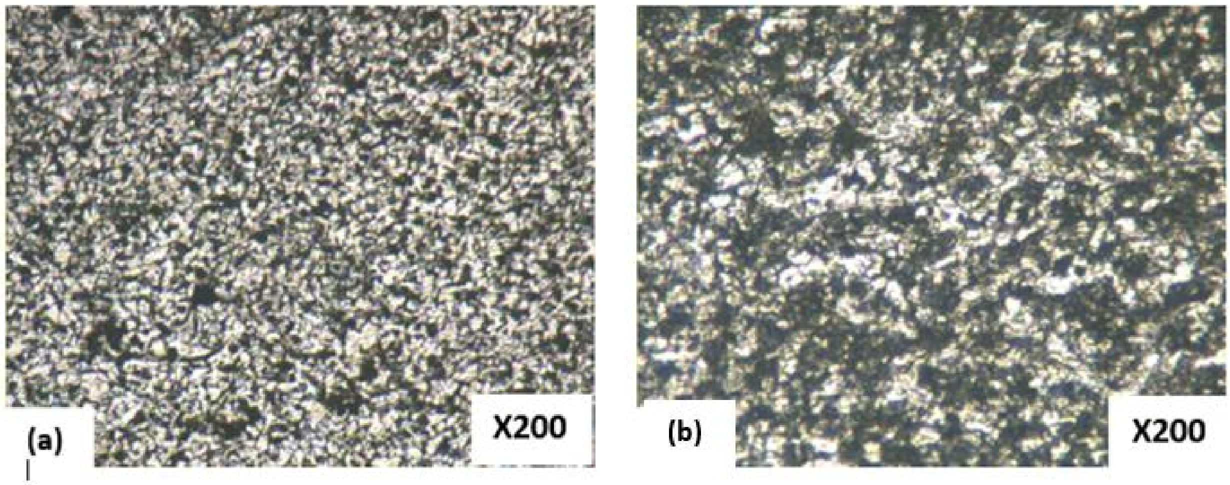

Figure 9: Micrograph of samples at 25% deformation (a) rolled and (b) rolled + stress-relief anneal

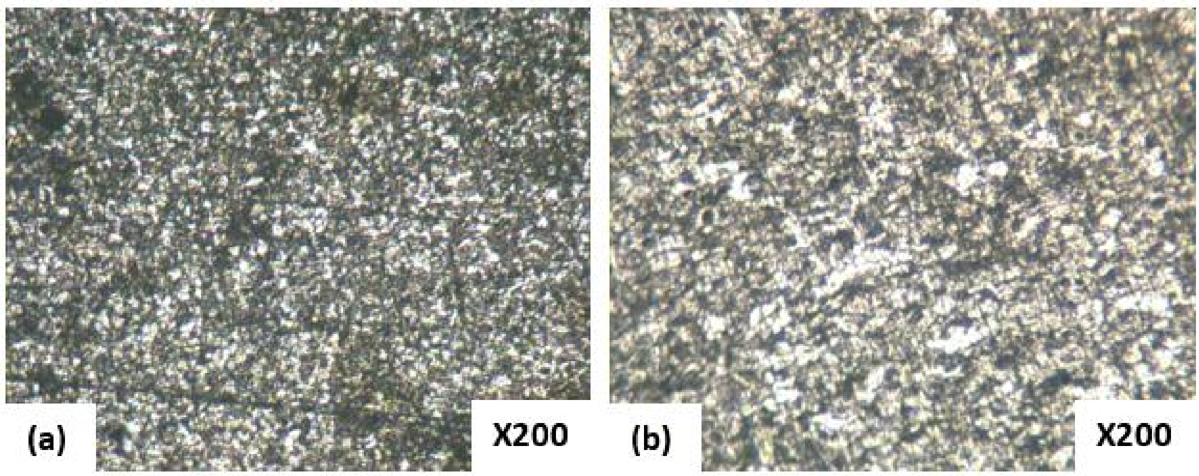

Figure 10: Micrograph of samples at 30% deformation (a) rolled and (b) rolled + stress-relief anneal

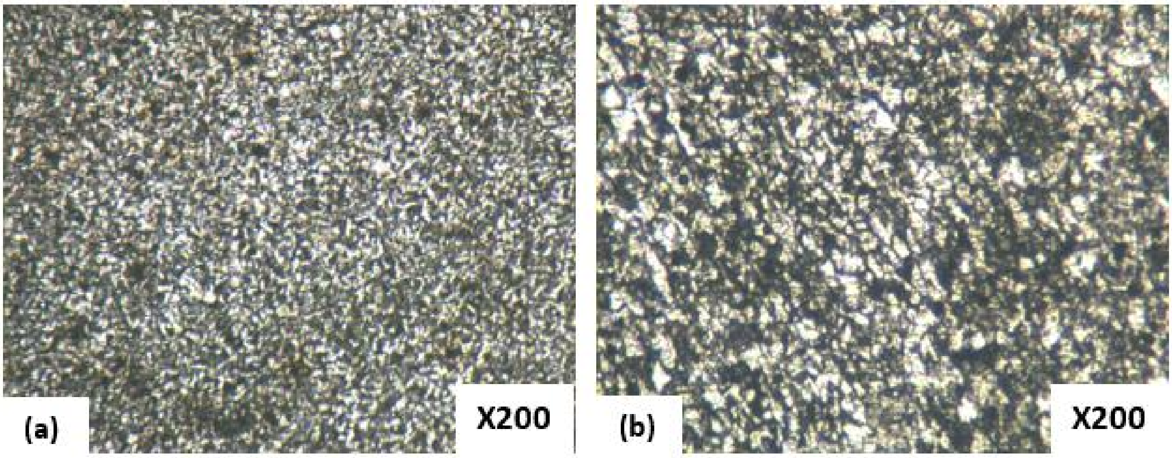

Figure 11: Micrograph of samples at 35% deformation (a) rolled and (b) rolled + stress-relief anneal

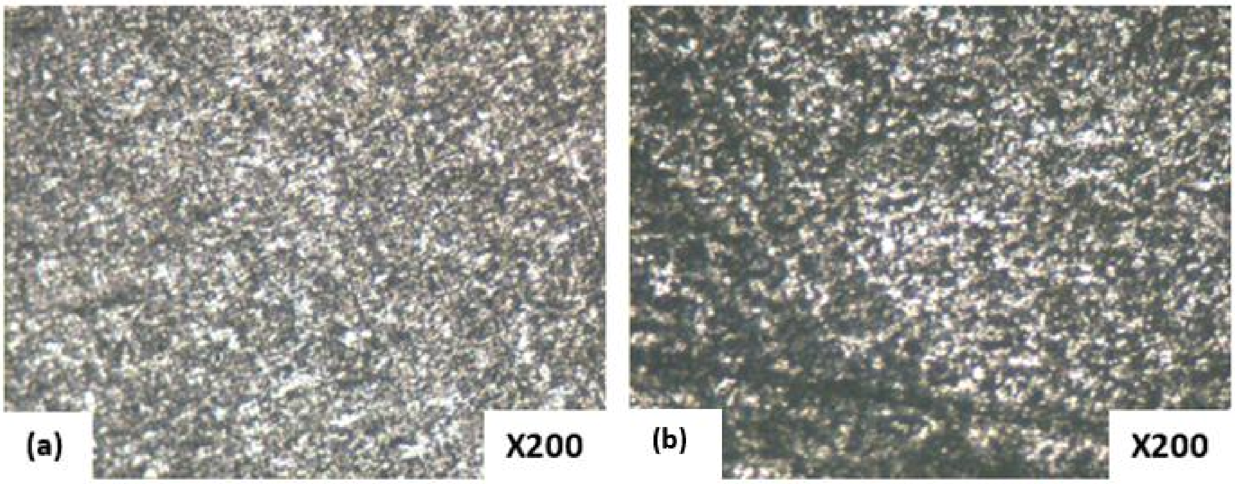

Figure 12: Micrograph of samples at 40% deformation (a) rolled and (b) rolled + stress-relief anneal

4. Conclusion

The mechanical and microstructural characterizations of a low carbon steel subjected to cold rolling and annealing heat treatment was carried out in this work. The outcome of the study showed that the stress relief annealing heat treatment caused significant change in the grain size, distribution and volume fractions of the phases present in the resulting microstructure. This is therefore responsible for the significant increase in the ultimate tensile strength (UTS), hardness, impact strength and percent elongation (ductility) of the low carbon steel. In addition, the heat treatment reduces the compressive residual stresses of the rolling, hence an increase in the degree of deformation has no significant effect on the UTS for the rolled + stress-relieved samples due to complete elimination of the strain hardening and induced residual stresses. Therefore, the outcome of the rolling and stress relief annealing in this work revealed the adaptability and hence the effective utilisation of the low carbon steel for structural applications when rolled and stress relieved.

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