Influence of cold working on Mechanical and metallographic characteristics of low carbon steel (S355)

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Abstract:

In the era of rapid industrialization various grades of steel is extensively utilized. This class of material is essentially imbibed with specific characteristics such as corrosion resistance behavior, good formability and high yield strength etc. The specific aim of this work is to analyze the effect of cold rolling process on the mechanical properties of low carbon steel grade S355. The prepared specimens undergoing the cold rolling process with 0 to 30% cold work percentage and was annealed at the temperature of 400°C for 1 hour. The ultimate tensile strength (tensile test), toughness (Charpy impact test) and hardness (Vickers test) of each specimen was conducted to analyze the Mechanical properties. Further microstructure analysis of the S355 steel before and after cold rolling treatment was conducted to characterize the material. The results enumerates that both tensile strength and toughness of material is augmented with increasing percent reduction in specimen thickness for 0 to 30 percent. Furthermore, the microscopic observation implies micro structural modification (elongation and compression of grains) and increase in the mechanical properties which justifies its application as a structural material.

Key words: Steel grade S355, Cold rolling, Tensile strength, Mechanical properties, Microstructure.

Introduction

Low carbon steel is a type of carbon steel with a low amount of carbon – it is actually also known as “low carbon steel.” Although ranges vary depending on the source, the amount of carbon typically found in low carbon steel is 0.05% to 0.25% by weight, whereas higher carbon steels are typically described as having carbon content from 0.30% to 2.0%. Low carbon content and additions of elements that have a strong affinity for carbon, such as niobium or titanium; have long been known to promote recrystallization textures favorable for severe forming operations with a high degree of tolerance to processing variables [1]. If any more carbon than that is added, the steel would be classified as cast iron. Low carbon steel is not an alloy steel and therefore does not contain large amounts of other elements besides iron; you will not find vast amounts of chromium, molybdenum, or other alloying elements in mild steel. Since its carbon and alloying element content are relatively low, there are several properties it has that differentiate it from higher carbon and alloy steels [2]. Less carbon means that low carbon steel is typically more ductile, machinable, and weldable than high carbon and other steels, however, it also means it is nearly impossible to harden and strengthen through heating and quenching. The low carbon content also means it has very little carbon and other alloying elements to block dislocations in its crystal structure, generally resulting in less tensile strength than high carbon and alloy steels [3]. Low carbon steel also has a high amount iron and ferrite, making it magnetic. The lack of alloying elements such as those found in stainless steels means that the iron in low carbon steel is subject to oxidation (rust) if not properly coated. But the negligible amount of alloying elements also helps mild steel to be relatively affordable when compared with other steels. The material used in this project is low carbon steel grade S355.This grade of material show great value for structural purpose. However, its main drawback is low tensile strength as compared to medium and high carbon steel. By using proper metal forming technique the mechanical properties can be improved. Among most of the metal forming processes cold rolling is one of the most suitable technique which results in improvement in mechanical properties as well as microstructure of material. Structure and resulting material properties are significantly influenced by cold rolling because in the given terms no recrystallization can occur. Extension of grains in the direction of rolling occurs and the arrangement of crystallographic lattice gets a directional character [4]. Banding character of other structural phases, such as of inclusions, pearlitic blocks, etc. has been developed too. Three types of texture (i.e. deformation, structural and crystallographic texture) arise, which yields in a directional character of mechanical properties. Heat treatment is included after cold forming for removal of anisotropy of properties. To factors influencing the microstructure after annealing are: the initial character of material structure before cold forming, the total cold reduction, annealing conditions (temperature and time) and also cooling speed. More and more progressive types of material have been used in this field of processing [5-8]. Many metals need to undergo plastic deformation (i.e. rolling, drawing, forging, etc.) to generate useful final products. In this study, attention will be given to the cold rolling process where the metal is passed between counter-rotating rolls. Cold rolling is carried out below ~0.3 Tm, where Tm is the absolute melting point of the metal. This process is widely used to make sheets and strips with superior surface finish and dimensional tolerance [9-13]. During deformation, the internal structure of a metal changes in several ways; the grains change their shape, total grain boundary area increases.

Many metals need to undergo plastic deformation (i.e. rolling, drawing, forging, etc.) to generate useful final products. In this study, attention will be given to the cold rolling process where the metal is passed between counter-rotating rolls [14]. Cold rolling is carried out below ~0.3 Tm, where Tm is the absolute melting point of the metal. This process is widely used to make sheets and strips with superior surface finish and dimensional tolerance [15]. During deformation, the internal structure of a metal changes in several ways; the grains change their shape, total grain boundary area increases, an internal substructure forms within each grain and point defects are generated. These structural changes are associated with the formation and accumulation of dislocations [17].

Most of the energy expended in cold deformation appears in the form of heat, with only a very small amount stored in the metal as strain energy associated with various lattice defects created by the deformation [18]. The amount of energy retained depends on the deformation process and a number of other variables, for examples, composition of the metal as well as the rate and temperature of deformation [8]. In cubic metals, there are two principle modes of deformation: slip and twinning. If the stacking fault energy is relatively high as in the case of low carbon steels, plastic deformation at normal conditions is only due to crystallographic slip (i.e. slip on planes and along directions fixed with respect to the crystal axis). Typical slip systems for BCC materials are on the {110}, {112} or {123} planes in the close packed directions [19]. During deformation, each grain tends to change its orientation with respect to the direction of the applied deformation which leads to a preferred orientation or texture as deformation proceeds. However, these changes in grains‟ orientation are not uniformly distributed since each grain of an aggregate is subjected to the constraints exercised by neighbor grains, each of which is deforming in a unique manner, thereby generating micro structural heterogeneities in the form of deformation bands, transition bands and shear bands [20]. The hierarchy of microstructure in polycrystalline metal deformed by slip was defined by, Ueji et al. [5]. At the smaller scale, dislocation cells, which comprise the smallest volume elements, are surrounded by single walled Dense Dislocation Walls (DDW) at low strain or double walled Micro Bands (MB) at medium strain. At high strain, the cell blocks become elongated and surrounded by lamellar dislocation boundaries (LB) which replaces the DDW and MB structure.

Based on the literature review, the present work is carried out to meet few specific objectives such as: analysis of important mechanical properties and microscopic observation on the low carbon steel S355 when subjected to different percentage of cold work. Further the observations recorded from known cold rolled material assist us to gain some insight on microstructure texture evolution in order to justify its viability as a structural material.

Material and method:

A sheet of low carbon steel with dimension 610*40*20 (L*W*H) is chosen to prepare test specimens. For perform cold rolling process at different reduction stages (10, 20, and 30) cut that sheet into four parts with the help of power hacksaw. Three sheet were cold rolled to three different reductions; 10%, 20% and 30%. Size of each sheet is equal with dimension 150*40*20 (L*W*H). A small amount of error in thickness was allowed for due to the difficulties of obtaining the exact desired amount of reduction. Cold Rolling was performed using a four-high rolling mill. Initial thickness of sheet is 20mm. Reduction in per pass is 0.5mm.The details of cold roiling process on low carbon steel is mentioned in table. 1 as:

Table. 1 The details of cold roiling process on low carbon steel specimens.

S. No	Material selected	Reduction (%)	Passes	Thickness (mm)
1	Low carbon steel	10	4	18
2		20	8	16
3		30	12	14

Static annealing was carried out for each sample from all the different reductions. Annealing is done after machining because during machining stress generated for minimize these stress annealing is done. The annealing temperatures used 400°C for low carbon steel. After annealing process furnace cooling is done for 25°C.

SPECIMEN PREPARATION

There are different types of specimen depending on the type of the grips and on the form of the available material (sheet, rod, etc.). Generally all specimens have two main parts, the gage section and the ends. The dimensions of the specimens are standardized (TS, DIN, ASTM, British standard etc.). Each standard may contain a variety of test standards suitable for different materials, dimensions and fabrication history. A standard specimen is prepared in a round or a square section along the gauge length as, depending on the standard used. Both ends of the specimens should have sufficient length and a surface condition such that they are firmly gripped during testing. It has two shoulders and a gage section in between.

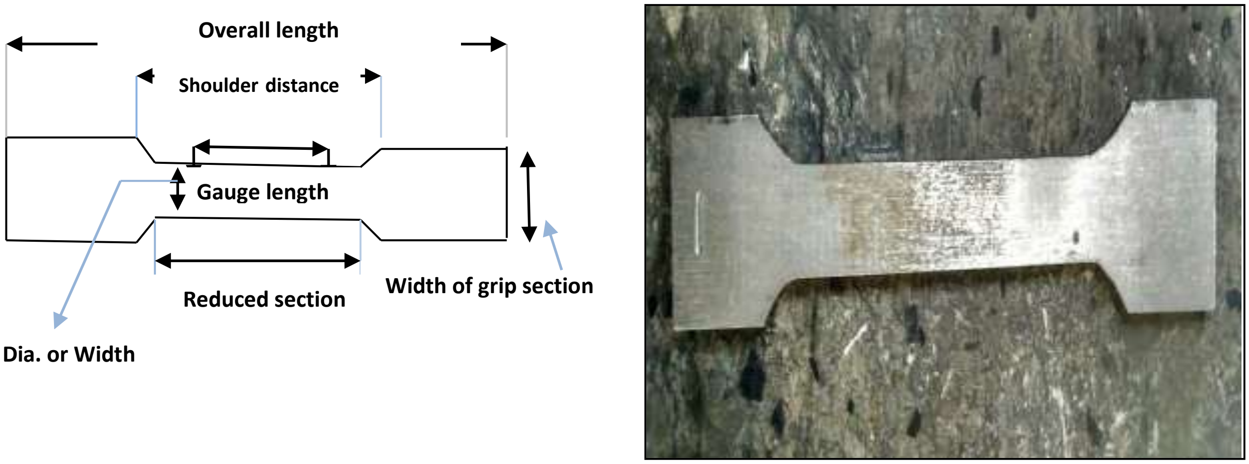

Figure: 1 Specimen terminology and prepared specimen of low carbon steel S35

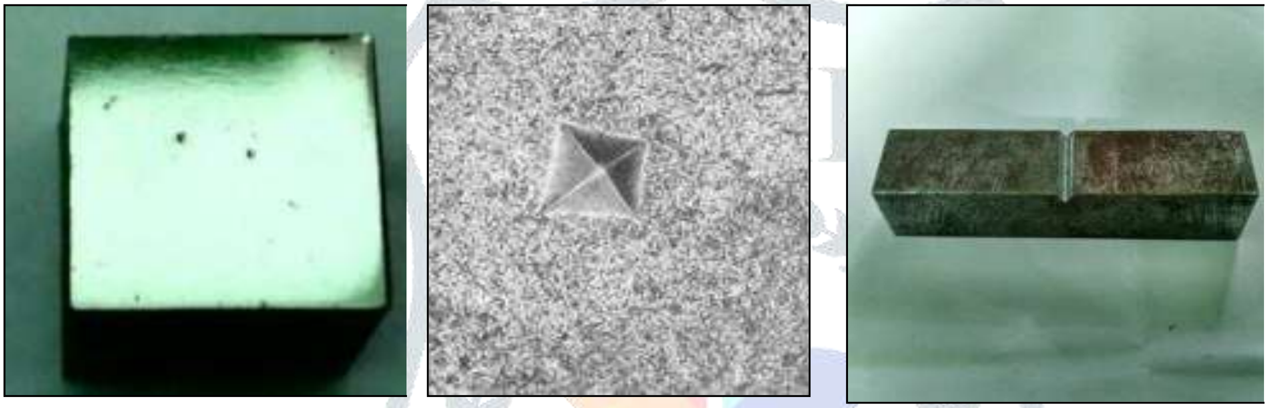

Figure: 2 Specimen of low carbon steel S355 for Vickers and Charpy test

Table. 2 Actual dimensions of prepared specimen of low carbon steel S355.

Overall length	Gap length	Width	Thickness	Grip Section	
152mm	80mm	10mm	4mm	Width	Length
				20mm	24mm

Test method

Initially all the length and diameter of the specimen are measured then mark the location of the gauge length along the parallel length of each specimen for subsequent observation of necking and strain measurement. After these initial fitments, grip the specimen on to the Universal testing machine (UTM) and tests were carried out by gradually applying the load by moving the upper jaw upwards with hydraulic piston. Record the graph of the rupturing load. Then open the data file in a graphing or spreadsheet program (e.g. Excel) checking that the load and displacement data columns are intact. Then, develop the following columns in addition to the data columns: engineering stress, engineering strain, true stress, and true strain. Develop and present the following plots such that in each plot both materials are shown:

- Load versus displacement for the entire displacement range.
- Engineering Stress versus engineering strain for the entire strain range tested.

- True stress versus true strain up to necking.

Determine the following for each data set (material) noting the proper units for each: 0.2% off set yield strength, ultimate strength, ruptures strength, modulus of elasticity, modulus of toughness, percent elongation. Determine percent reduction in area only for the specimen tested by the group.

Vickers and Charpy hardness test

The Vickers hardness test method consists of indenting the test material with a diamond indenter, in the form of a right pyramid with a square base and an angle of 136 degrees between opposite faces subjected to a load of 1 to 100 kgf. The Vickers hardness value (VHN) can be calculated from the applied load divided by areas of indentation, at which the latter is derived from the diagonals of the pyramid as expressed in the equation below.

$$VHN = \frac{2P\sin\left({}^{\alpha}/_{2}\right)}{d2} = 1.8544P/d2$$

The Pyramid indentation of test specimen is shown in figure.2 for measurements.

Impact tests determine impact toughness, a material property, most commonly by measuring the work required to fracture a test specimen under impact. The most common impact test is the Charpy impact test. The Charpy impact test is a high strain rate test that measures the work required to rupture a specimen in flexure. Charpy specimens are uniform, rectangular prismatic specimens with one notch per specimen to encourage rupture. The Charpy testing machine is comprised essentially of a hammer with a striking head (a wedge shaped head was used in this laboratory) attached to a nearly frictionless pendulum with a known potential energy. This test is performed on. The prepared test specimens are shown in figure.2.

MICROSCOPIC OBSERVATION

Metallographic is the study of the structure of metals and of metal alloys through the examination of specimens with a metallurgical microscope. The structures observed in the microscope are often recorded photographically. The metallographic examination of specimens allows the metallographer to observe and record the crystalline structures and to interpret from them the history of manufacture and use of the material. The metallurgical microscope for metallographic observations is shown in Figure. 3.

Figure. 3. Representing Vickers hardness tester and optical micrograph.

RESULT AND DISCUSSION

The mechanical properties mainly affected by the percentage of cold rolling, as the case may be, for low carbon steel.

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Effect of cold rolling on hardness of low carbon steel

Figure. 4, shows the hardness of low carbon steel samples after various stages of cold rolling and the corresponding values are depicted in table.3. From this figure it can be seen that as the level of reduction increases the hardness increases due to the increase in the dislocation density.

Table. 3 Data table for hardness of test specimen

%cold reduction	0	10	20	30
Hardness(in HV10)	135	208	218	235

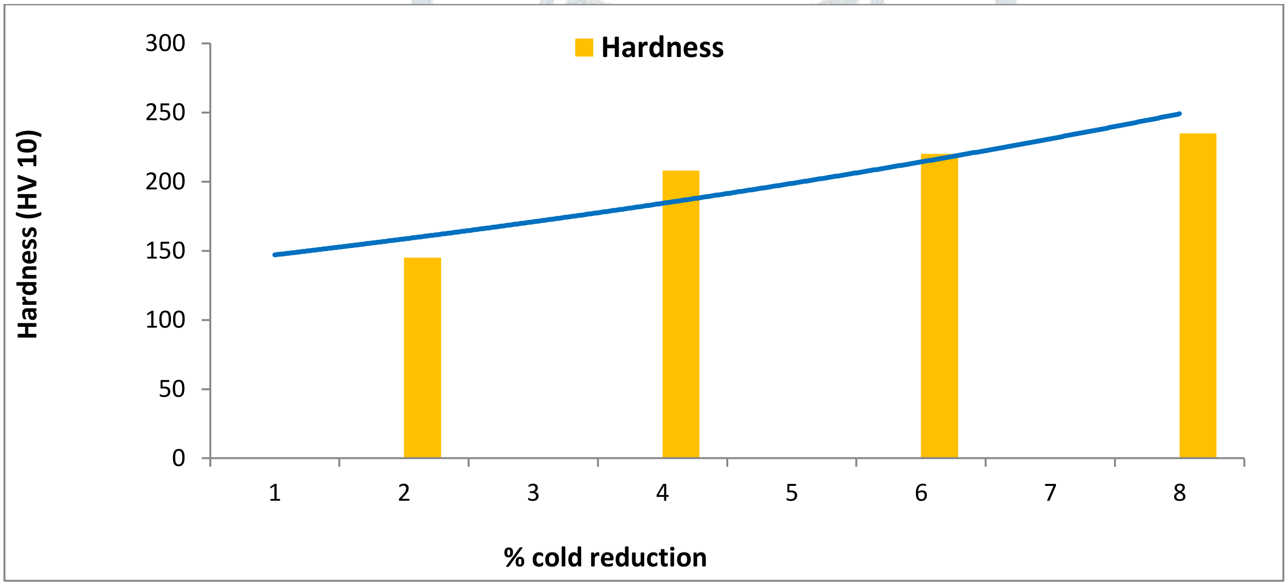

Figure. 4: Variation in Hardness of low carbon steel samples after various stages of cold rolling.

The hardness of the samples after various stages of cold rolling and subsequent annealing were measured increases the hardness of low carbon steel due to the increasing of deformation. This is in turn corresponded to the strain hardening as a result of cold rolling which leads to reduce the thickness of steel sample. Moreover, the interactions between the particles and the dislocations involved in the deformation of low carbon steel are responsible for the greater increase in hardness compared with the IF steel.

Effect of cold rolling on toughness of low carbon steel

The toughness of the samples after various stages of cold rolling and subsequent annealing were measured. Figure.5, shows the toughness of low carbon steel samples after various stages of cold rolling and the corresponding values are depicted in table.4 . From this figure it can be seen that as the level of reduction increases the toughness decreases due to the increase in the dislocation density.

Table. 4 Data table for toughness of test specimen

%cold reduction	0	10	20	30
Toughness (Joules)	42	34	28	24

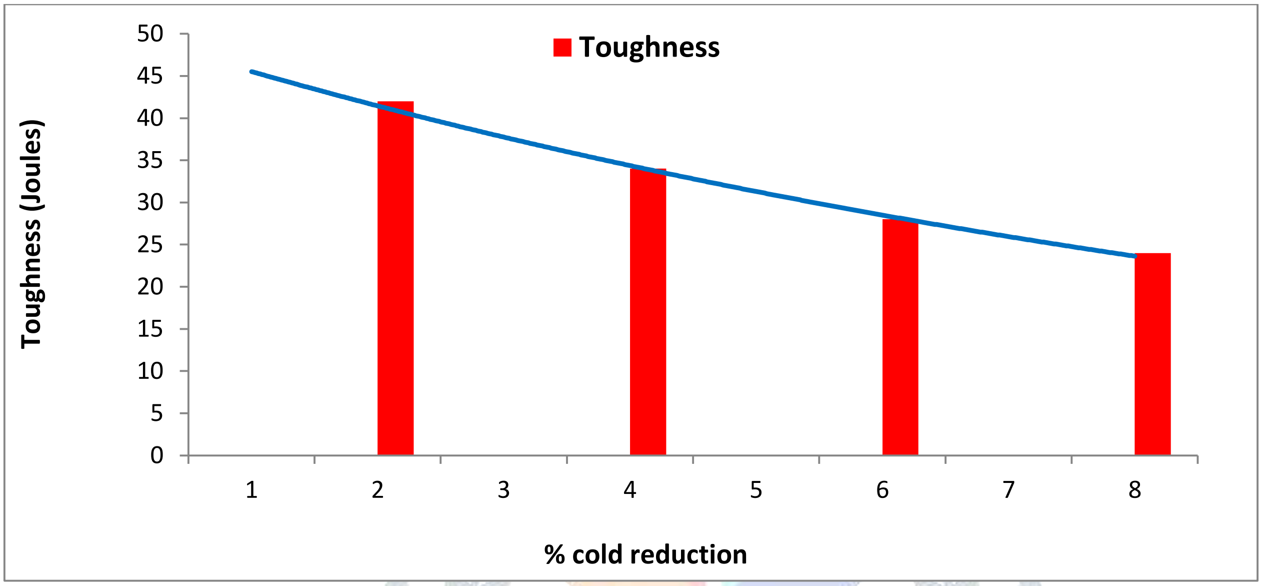

Figure. 5: Variation in Toughness values of low carbon steel samples after various stages of cold rolling.

The toughness of the samples after various stages of cold rolling and subsequent annealing were measured which was found to decrease the toughness value of low carbon steel due to the increasing of deformation.

Effect of cold rolling on tensile strength of low carbon steel

The tensile strength of the sample after various stages of cold rolling and subsequent annealing were measured on UTM.

Table. 5 Data table for tensile strength of test specimen

%cold reduction	0	10	20	30
Tensile strength (MPa)	602	776	816	841

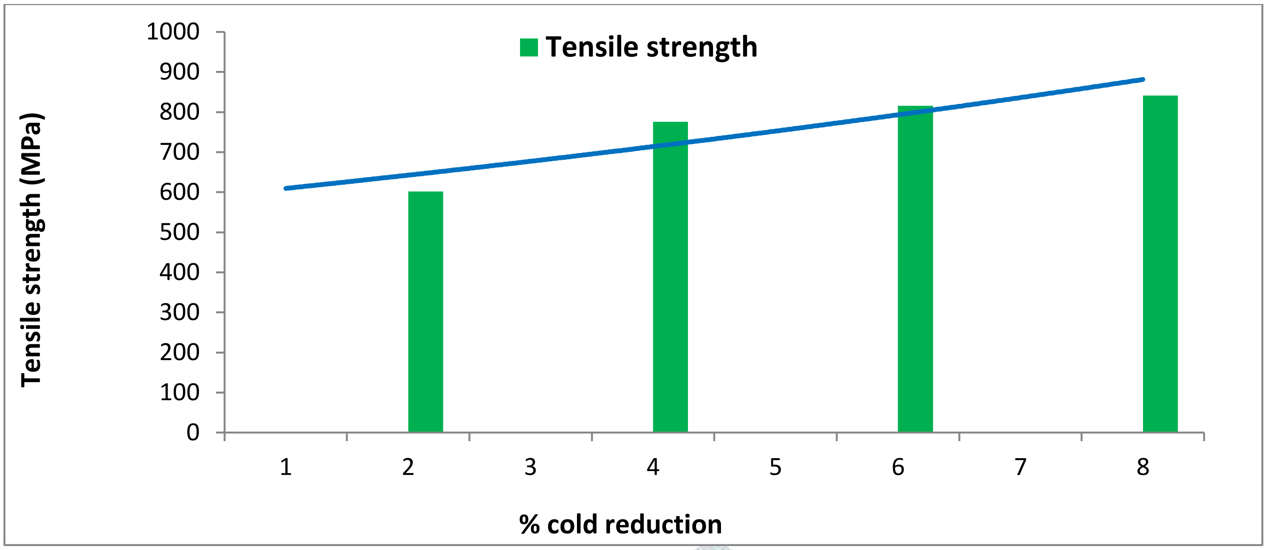

Figure. 6: Variation in tensile strength values of low carbon steel samples after various stages of cold rolling.

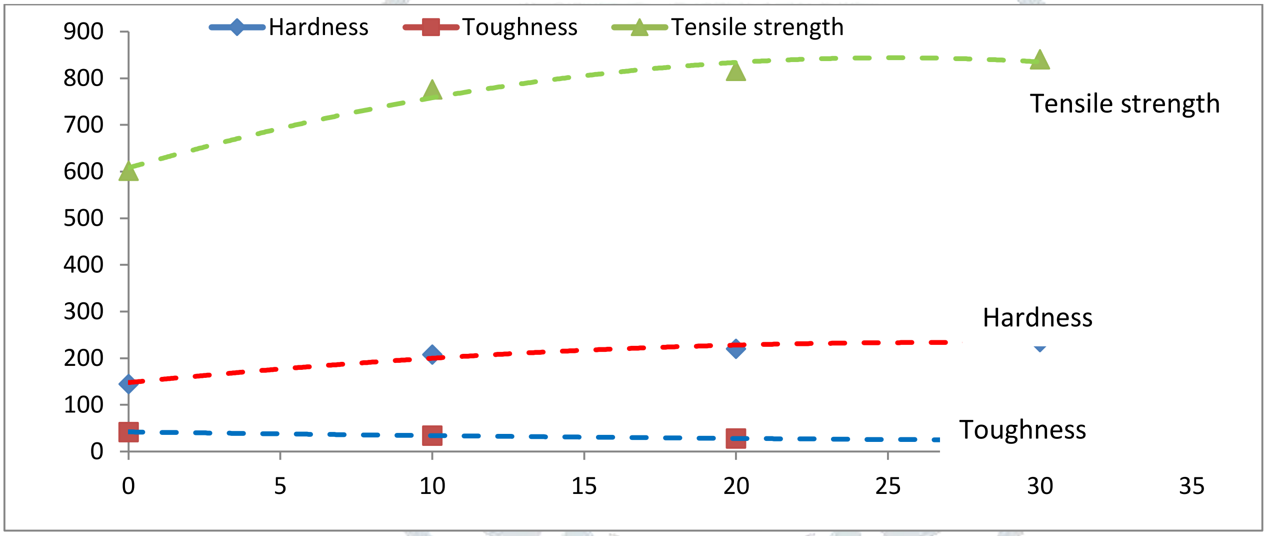

Figure. 7: Effect of cold rolling on the mechanical properties on low carbon steel

Figure.6, show relationship between the tensile strength vs. cold rolling reduction at various stages (10, 20, and 30) and the corresponding values are depicted in table.5. When material is cold worked, the crystal structure of the metal is deformed (*bent*, *twisted*, *compressed*, *etc*., resulting in the relatively uniform crystalline plains (from a recrystallization anneal) moving over and past one another. This movement creates imperfections; these discontinuities in the structure are *dislocations*. These dislocations provide further resistance to deformation, which can be seen as an increase in hardness, as measured by the penetration of an indenter under load. The ultimate tensile strength, and yield strength also increase due to the "locking effect" of those distorted and twisted grains (metallic crystals).

The elasticity limit is defined as the point of transformation of the elastic deformation into plastic deformation. The yield strength of the low carbon steel minimizes with the incrementing percentage of cold rolling, which in turn truncates the ductility of material and induct the brittleness in material because of the strain hardening as a result of cold rolling, which in turn truncates the ductility of material and induct the brittleness in material because of the strain hardening as a result of cold rolling. Further, the incrementing of percentage cold rolling abbreviates the tensile strength due to strain hardening and makes the material brittle as well as for the same reasons deal with yield strength. Figure.7, show the incrementing in percentage of cold rolling leads to increase in hardness and tensile strength but decline in material toughness.

MICROSCOPIC OBSERVATION

Steels were cold rolled to reductions of 10%, 20%, and 30%. The effect of different reductions on the microstructure can be seen in Figure for the low carbon steel, respectively. These figures show that the grains became more elongated along the rolling direction as the reduction level increases. The elongated sub grains are separated by much sharper boundaries than the other grain which indicate higher disorientations between neighboring sub grains and, hence, higher stored energy.

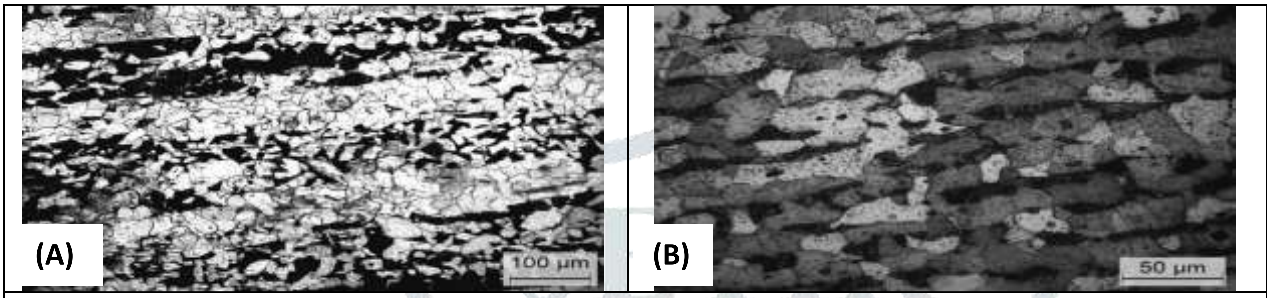

Figure. 8 (A, B). Microscopic image of annealed low carbon steel at (A) 100µm and (B) 50µm.

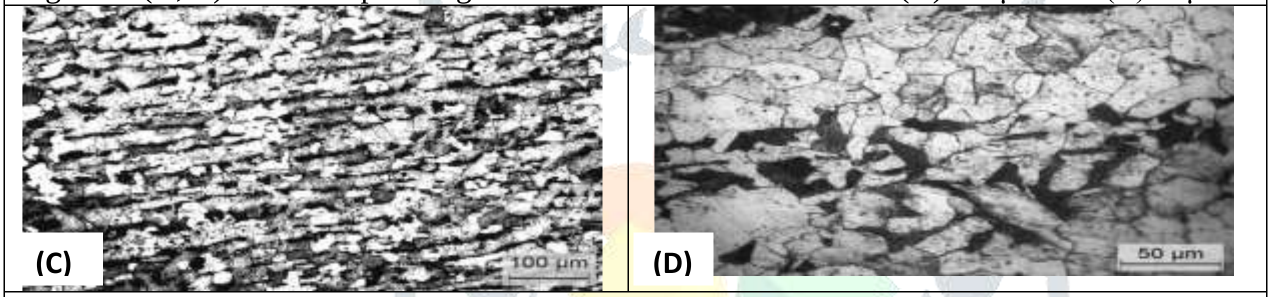

Figure. 8 (C, D). Microscopic image of 10% cold rolled annealed low carbon steel at (A). 100µm and (B) 50µm.

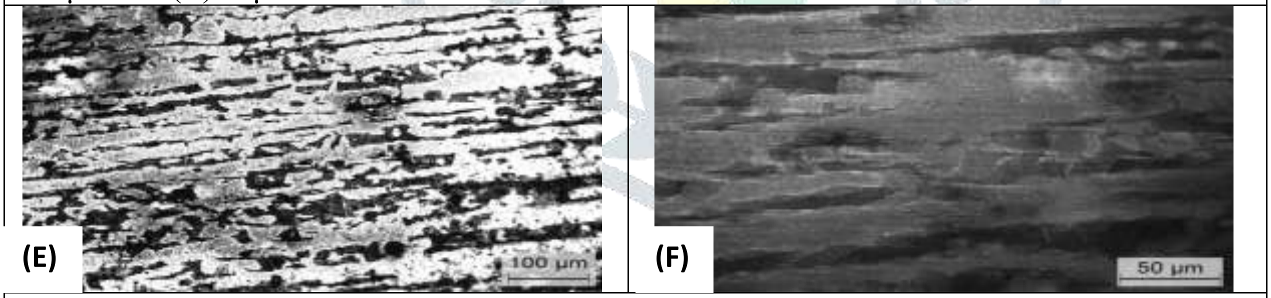

Figure. 8 (E, F). Microscopic image of 20% cold rolled annealed low carbon steel at (E). 100µm and (F) 50µm.

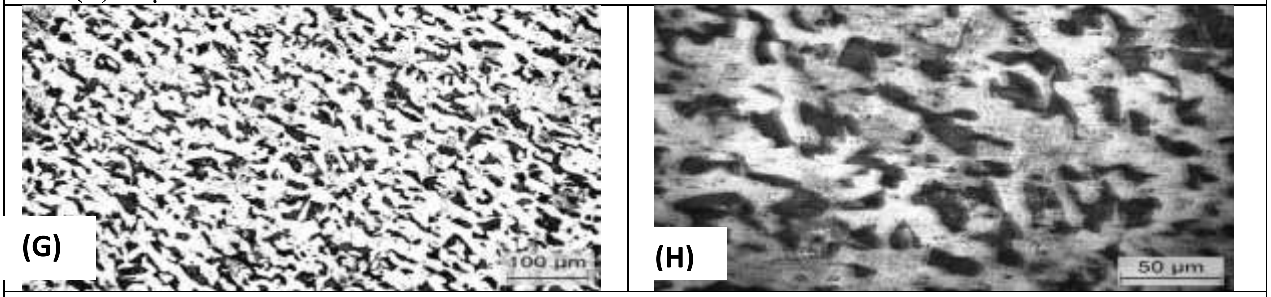

Figure. 8 (G, H). Microscopic image of 30% cold rolled annealed low carbon steel at (G). 100µm and (H) 50µm.

Figure. 8. Microscopic image of 10%, 20% and 30% cold rolled annealed low carbon steel at 100µm and 50µm.

During cold rolling, elastic deformation initially occurred as progressive grain elongation in the parallel direction of cold rolling. As a percentage of cold rolling increases this may leads to the transition from the elastic deformation to the plastic deformation as a point of elasticity as a yield point is disunited between them. The specimens to evaluate the structure by optical microscope after cold rolling were consisted of the fine grains of the ferrite with minor grains of pearlite. Incrementing the percentage of algid rolling leads to increment the elongation of ferrite and pearlite grains, which in turn prodigiously affected the mechanical properties; this is concurred with the earlier research work. [12].

Despite ductility decrease or increase accompanied by loss of strain-hardening capacity, the fracture features present a ductile characteristic with numerous diminutive and sizably voluminous dimples (Fig. 8 A-H). Spherical crack areas at the surface fractures designate that dimple fractures are controlled by nucleation, magnification, and micro-void coalescence during the necking phenomenon of tensile deformation. Fracture morphology of the sample in Fig. (8A-D) pellucidly shows numerous dimples with some more diminutive voids at the grain boundary and some more astronomically immense voids in the pearlite regions. The voids nucleated and grew in regions of high stress concentration at the boundaries between the ferrite matrix and the grains [35] that consist of numerous carbide precipitates with high strain energy [21]. However, only a few fine dimples optically canvassed under high magnification (Fig. 8 E-H) can be attributed to the minimized capacity for plastic deformation, as denoted by the low ductility during cold rolling process.

Conclusion

Impact of cold rolling on mechanical properties and microstructure of low carbon steel was studied. The Annealed specimens with refined microstructure showed typical tensile properties of ultra-fined steels with lack of excessive work hardening and increased ductility. The tensile strength dropped after annealing and re-crystallization due recovery from stressed conditions. However, increased fracture strains reflect their improved formability essentially required for structural applications of steel. The optical metallography of the rolled specimen showed elongation of the grains and increase of aspect ratio along the rolling direction. The micro structural observations of the annealed specimens clearly revealed the re-crystallizations. The stress needed to increase the strain beyond the proportionality limit in the material continues to rise beyond the proportionality limit indicating an increasing stress requirement to continue straining. It has been observed that mechanical properties like tensile strength and hardness increases with increasing percentage of cold reduction while the toughness of material reduces with subsequent increase in percentage cold reduction. The difference in yield strength was attributed to the strain hardening, resulting from the different degrees of cold deformation.

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