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Mechanical Properties of Cold-Drawn Low Carbon Steel for Nail Manufacture: Experimental Observation

N.A. Raji and O.O. Oluwole
Mechanical Engineering department, University of Ibadan, Nigeria

Abstract: The objective of this study is to investigate the influence of service situation on the mechanical properties of plain nails manufactured from low carbon steel. The influence of the degree of cold drawing on the mechanical properties and strain hardening of the material is investigated by tensile test experimentation. The stress-strain relationships of the cold-drawn low carbon steel were investigated over the 20, 25, 40 and 55% degree of drawn deformation for the manufacture of 4, 3, 2½ and 2 inches nails, respectively. The true stress-strain curves were analyzed to obtain the yield strength and tensile strength of the cold drawn steel. It is shown that the yield strength, tensile strength, hardness and toughness of the low carbon steel reduce with increasing degree of cold-drawn deformation. The micrographs of the deformed samples obtained using optical microscope shows that the grain structure elongates in the direction of the drawing operation and misorientation of the grains set in at 40 and 55% degree of deformation. The difference in yield strength was attributed to the strain hardening, resulting from the different degrees of drawn deformation.

Keywords: Cold-drawing, hardness, tensile strength, tensile test, toughness, yield strength

INTRODUCTION

Nails are driven fasteners used mostly in wood structures. They consists of a metal rod or shank, pointed at one end and usually having a formed head at the other, that can be driven by hammering into pieces of wood or other materials to fasten them together. A nail is usually made of steel, although it can be made of aluminum, brass, or many other metals. Nails are produced uncoated (bright) or with any of several different coatings such as zinc (to retard corrosion), cement (to provide better adherence in the wood or other material into which the nail is to be driven) and paint (for improved appearance). The head, shank and point may have several shapes based on the intended function of the nail. Nails are divided into three broad categories based on their length. In general nails less than 1 inch (2.5 cm) in length are called tacks or brads. Nails 1-4 inches (2.5-10.2 cm) in length are called nails, while those over 4 inches (10.2 cm) are some-times called spikes. The length of a nail is measured in a unit called the penny. The symbol for penny is "d".

During the manufacturing process, coils of wire are produced by drawing steel rod stock through a series of dies to the diameter required for nail manufacturing. The steel wire is compressed along the major axis to form the nail head and pinched on the opposite end to form the point. The basic nail that produces a bright nail, in order to produce various characteristics nail, may be further treated in numerous ways after being formed. They may be heat treated, treated to prevent rust and/or corrosion, or coated with various substances. Once the nail is formed, it may also go through a mechanical deformation process whereby threads are rolled into the shank surface. This last step is what differentiates “deformed-shank” (or threaded-shank) nails from plain-or smooth-shank nails (Wills *et al*., 1996). Most steel nails are produced from steel wire. Some producers of wire nails use purchased steel wire as a starting raw material and are known as nonintegrated producers, whereas some producers utilize their own facilities to produce wire for nails, using steel wire rod as their starting material; these producers are called “integrated producers.” The common plain-shank nails for general construction work of interest are usually manufactured from mild steel containing 0.16-0.29% cold worked annealed wire.

In the Nigerian market, nail product of carbon steel is characterized by buckling and sometimes brittle fracture. These problems have encouraged massive importation of foreign made nails from developed countries like china, Canada and the United State of America which has resulted in a huge amount of foreign exchange loss to the Nigerian economy and less trust in made in Nigeria nails. The demand for local mass-produced commodity nails is dependent on the fluctuations in the market, which varies with the economy subject to this competition from foreign manufacturers tending to reduce profits.

The cold-drawing nail manufacturing process is characterized by microstructure changes which affect its mechanical properties and consequently the product

Corresponding Author: N.A. Raji, Mechanical Engineering department, University of Ibadan, Nigeria

resulting from the process. The wire hardens during plastic deformation and the ductility is reduced while the tensile strength increases. The structural hardening is due to the movement of dislocation and the generation of additional dislocation within the material structure. This defect is known as strain hardening and is usually accompanied with reduced ductility of the material (Phelippeau *et al*., 2006). The distorted, dislocated structure resulting from cold working of the metal becomes unstable due to the strain hardening effect.

The structural changes which occur during the cold deformation involve gradually stretching of the grains in the direction of the principal deformation and at the same time the development directional arrangement of the crystallographic lattice. A typical feature of such deformed structure is the anisotropy of the mechanical properties (Fuller and Brannon, 2011).

The effects of cold work on the properties of polycrystalline structures have been studied extensively (Zaefferer *et al*., 2003; Ganapathysubramanian and Zabaras, 2004; Prasad *et al*., 2005; Dománková *et al*., 2007; Huda, 2009; Pawlak and Krzton, 2009; Schindler *et al*., 2009; Wert *et al*., 1997; Godfrey *et al*., 2001; Maurice and Driver, 1997; Bossom and Driver, 2000; Godfrey *et al*., 1998; Hansen and Huang, 1998). The metal microstructure forms a topological network with a specific number of elements (Barrales-Mora *et al*., 2008).

Influence of cold work and aging on the mechanical properties of Cu-bearing HSLA steel was studied by (Panwar *et al*., 2005). It was concluded that cold working and subsequent aging enhances the hardness and Tensile Strength (UTS) of the material but significantly deteriorate the ductility and impact energy. The poor impact energy is a consequence of inhomogeneous deformation at coherent particle sites and high stress concentrations at dislocation-precipitate junction and dislocation cell walls. Schindler *et al*. (2006) investigated the impact of cold reduction size and annealing on the mechanical properties of HSLA steel. It was confirmed that by a suitable combination of size of previous cold deformation and parameters of annealing properties, it is possible to influence considerably a complex of mechanical properties of particular strips of the steel.

Samuel *et al*. (2010) applied High Intensity Electric Pulse (HIEP) to a severely deformed eutectoid microstructure in the high carbon steel wire. The process resulted in spheroidised microstructure. The observed spheroidisation on electropulsing was compared with that reported for isothermal/thermo-mechanical annealing of the pearlite structure discussed in (Zelin, 2002). The faster kinetics observed in the study was rationalized in terms of accelerated kinetics induced by high intensity electric pulse HIEP.

Heat treatment procedure known as annealing has been successfully used to modify defects and improve the mechanical properties of the cold deformed material (Janošec *et al*., 2007). Annealing is a heat treatment procedure wherein a material is altered causing changes in its properties such as strength and hardness. It is used to induce ductility, soften material, relieve internal stresses and refine the structure by making it homogenous and improved cold working properties.

An understanding of the phenomenon involved in the effect of the cold drawing operation on mechanical properties of the low carbon steel for nail manufacture can therefore not be over emphasized in order to find the right heat treatment procedures for the local nail industries so as to meet the stringent operating conditions and compete favorably with foreign nail manufacturers. The major objective is to improve the quality of nails produced in the country by improving the properties of the product as might be demanded by the end users which could be achieved by optimizing the heat treatment process of the manufactured nails.

This study discusses the effect of cold drawing on the mechanical properties of low carbon steel used for nail manufacture.

EXPERIMENTAL PROCEDURE

Commercially available wire rod of 5.5 mm nominal diameter drawn to 4.2, 4.0, 3.24 and 2.35 mm diameter for the manufacture of 4, 3, 2½ and 2 inches nails, respectively were obtained for the experiment from Nigeria Wire Industry Ltd, Ikeja. The degree of cold-drawn deformation for each of the nail size is obtained from the expression (Huda, 2009):

$$\%\,Cold\ work = \frac{A_0 - A_d}{A_o} x100 \tag{1}$$

where, A_o is the original cross section area of the wire before deformation and A_d is the cross section area of the wire after deformation.

Specimens were cut from the various cold drawn steel and subjected to metallographic analysis and tensile test. The grain shape and grain size of the specimen were analyzed from the micrograph obtained for the 20, 25, 40 and 55% degrees of cold-deformation as shown in Fig. 1-4. Stress-strain curve is obtained for each of the deformed specimen to study the effect of the deformation on the yield strength, tensile strength, toughness, ductility and hardness of the steel. The energy absorption at the various degrees of cold-drawn deformation was obtained by determining the area under the stress-strain curve of the material using the strain energy equation (Murty, 2011) expressed as:

$$U = \int_0^{\epsilon} \sigma_e \, d \in \tag{2}$$

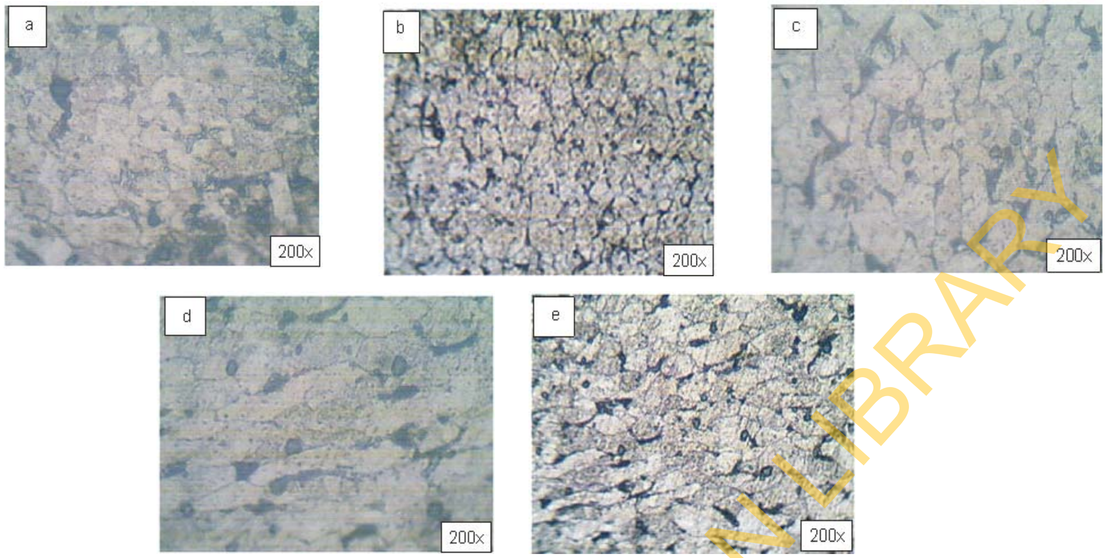

Fig. 1: Microstructure of samples cold-drawn at different degrees (a) Control sample, (b) 20% degree deformation, (c) 25% degree deformation, (d) 40% degree deformation, (e) 55% degree deformation

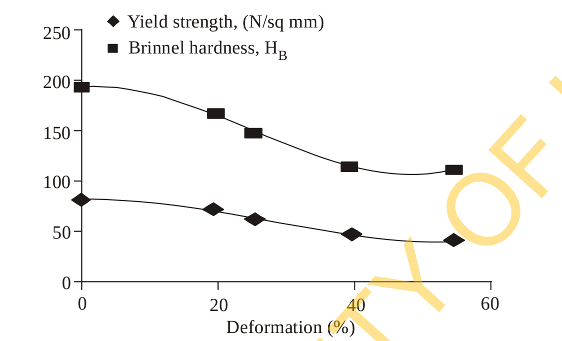

Fig. 2: Influence of % degree of cold-drawn deformation on yield strength and hardness of low carbon steel

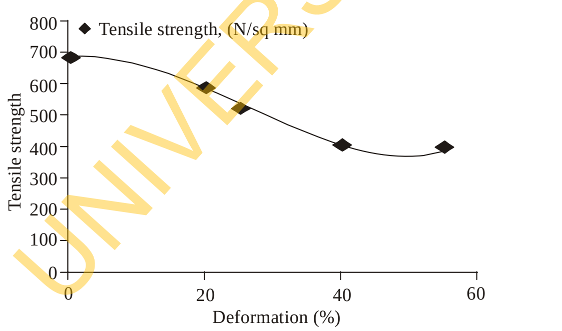

Fig. 3: Influence of % degree of cold-drawn deformation on tensile strength of low carbon steel

RESULTS AND DISCUSSION

The interpretation of the mechanical properties of the cold drawn low carbon steel is tabulated in Table 1. Figure 1a-1e show the micrographs of the steel at 0, 20, 25, 40 and 55% degrees of deformation, respectively. It is observed from the micrograph that the grain structure elongates in the direction of the cold drawing deformation. The elongation of the grains increases with increasing degree of deformation. Grains misorientation is observed for the 40 and 55% degrees of deformation. This implies that deformation at the 40 and 55% approaches the severe plastic deformation stage which is often associated with rotation of grains. This is expected to have considerable effect on the anisotropic nature of the mechanical properties of the steel. The effect of the structure changes due to this cold drawn deformation is established from the tensile test.

Figure 2 show the effect of the different degrees of cold-drawn deformation on the yield strength and hardness of the steel. The yield strength and hardness of the material reduces with increasing degree of deformation. The tensile strength of the steel also decreases with increasing degree of cold deformation as shown in Fig. 3. These could be attributed to the increasing strain hardening of the metal as the deformation increases resisting further tensile deformation thereby making the steel approach brittleness.

Figure 4a-4d are the log-log plots of the true stress-strain data for the low carbon steel. The increasing strain hardening parameters as shown on the plots is a measure of the resistance to further yielding of the material confirming its approach to brittle nature as the degree of cold deformation increase. The values of the strain hardening parameters as shown in Table 1 increases with increasing degree of cold deformation indicating the resistance to yielding due to the strain hardening effect of the cold study.

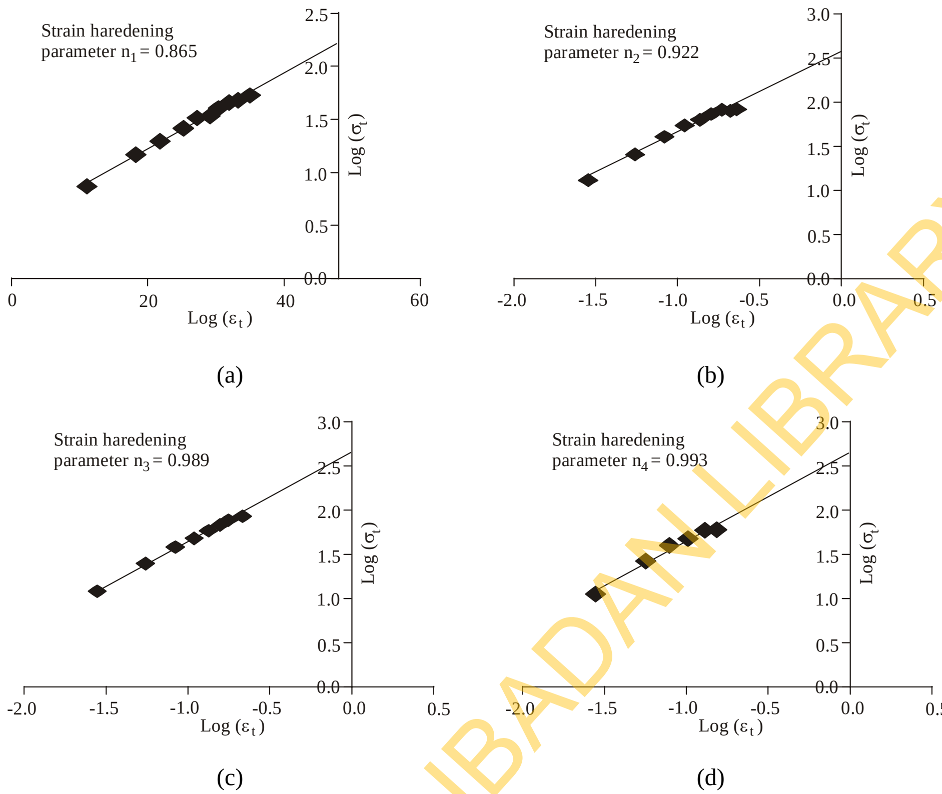

Fig. 4: Log-log plots of the true stress-strain data for the low carbon steel at different cold-drawn degree of deformation (a) 20% deformation, (b) 25% deformation, (c) 40% deformation, (d) 55% deformation

Table 1: Yield strength, ultimate tensile strength, toughness, brinnel hardness and strain hardening parameters of the nails at different degrees of drawn deformation

% deformation	Yield strength,σy (N/ sq. mm)	UTS (N/ sq. mm)	Modulus of toughness	Brinnel hardness (H_B)	Strain hardening parameter, n
Control specimen	80.0	670.88	32.88	194	-
20	70.0	578.79	19.42	168	0.865
25	60.0	510.12	11.25	148	0.922
40	44.5	392.40	8.58	114	0.989
55	40.0	382.59	4.57	111	0.993

In Table 1 it is shown that the modulus of toughness which is the energy needed to completely fracture the material reduces with increasing degree of drawn deformation. Materials showing good impact resistance are generally those with high moduli of toughness. This implied that as the degree of drawn deformation increases, the ability of the material to resist impact loading reduces. This could be said to account for the buckling or sudden fracture of some of the nails when hammered in service.

CONCLUSION

Nails are driven fasteners used mostly in wood structures. During the manufacturing process, coils of wire are produced by drawing steel rod stock through a series of dies to the diameter required for nail manufacturing. This manufacturing process causes microstructure changes such as grain elongation and grain misorientation of the low carbon steel. The toughness of the steel reduces as the degree of drawing deformation increases. 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. The degree of drawn deformation affects the yield strength, tensile strength and hardness of the material as evident in the flow curve analysis. The difference in yield strength was attributed to the strain hardening, resulting from the different degrees of drawn deformation.

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