THE EFFECT OF FULL ANNEALING ON THE MICROSTRUCTUR AND MECHANICAL PROPERTIES OF COLD DRAWN LOW CARBON STEEL

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ABSTRACT

The aim of this work is to determine the mechanical properties of cold drawn low carbon steel subjected to full annealing. The specimens were slowly heated up to a temperature of 900°C followed by soaking treatment of 60 minutes under this temperature in a muffle furnace. Tensile, charpy and Brinnel hardness tests were conducted to determine the yield strengths, tensile strengths, impact strengths, and hardness of the annealed steel. The yield strength, tensile strength, hardness and toughness of the nail are greater in the non-treated nails when compared to the fully annealed nails at 60 minutes soaking time. The microstructure analysis showed that rate of grain nucleation and recrystallization increased with increasing degree of cold-drawn deformation. Grain growth was observed at higher degree of deformation leading into reduction in the mechanical properties of the material. It is evident from the resulting mechanical properties of the nails and the microstructure analysis that desired properties of the nails could be obtained by controlling the microstructure evolution of the low carbon steel in annealing.

Keywords: annealing, strength, microstructure, grain size, grain growth, cold-deformation, recrystallization, nails.

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. Nail is usually made of steel, aluminum, brass, or other metals can be used as well depending on the area of application. Nails are produced uncoated (bright) or coated with zinc to retard corrosion, and to provide better adherence in the wood or other material into which the nail is to be driven. 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". 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".

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 is a cold deformation process. Structural changes occur during this cold deformation, in which grains forming the basic matrix of the material are gradually stretched in the direction of the principal deformation and at the same time directional arrangement of the crystallographic lattice is developed. A typical feature of such deformed structure is anisotropy of its mechanical properties. An initially isotropic material responds by developing anisotropy when subjected to inelastic deformation. The inelastic induced anisotropy includes directional anisotropy in cold worked metals Fuller and Brannon (2011). The steel wire is then compressed along the major axis to form the nail head and pinched on the opposite end to form the point. The basic material that produces a bright nail, for 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 low carbon steel containing 0.16–0.29% C cold worked annealed wire.

The wire-drawing of steel is an industrial plastic deformation process which leads to the structural hardening of the metal. The drawing process is considered to be one of the most effective and flexible methods to improve surface finish, obtain precise dimension and obtain the specified mechanical properties of a product Sawamiphakdi et al., (1998).

Mechanical properties distributions on the cross sections of drawn products were investigated by Luksza et al., (1998). Specific effective strain non-uniformities were found to influence the distribution of the mechanical properties in the final product of the drawn bars. It was noticed that the non-uniformity of mechanical properties in bars before deformation and different character of strain hardening of the bars after deformation were contributing factors to the influenced mechanical properties of the resulting product Luksza et al., (1998).

The rate of deformation as defined by the die angle contributes to the state of the non-uniformity of the bar. Knap, (1996) investigated the influence of die angle on the drawing parameters especially drawing stress during the drawing of square twisted wire used for twisted nails. Conditions were formulated for the stable deformation of the bars. An important characteristic of the drawing process is the die semi-angle, which influences the drawing forces, lubrication in the process and also the mechanical properties of the final product de Castro et al., (1996). Plastic deformation is controlled by the interaction of dislocations with the host lattice, the applied stress, and with other defects, such as dislocations, solutes, grain boundaries and precipitates Woodward, (2005). The cold work process of wire drawing consists of reducing the cross-section of a wire by pulling the wire through series of conical dies.

Metal wire drawing technology has been widely used to manufacture fine wires (Popova et al., (2004)). When the deformation amount is very significant, the wire generates microstructure heterogeneities that may exhibit large orientation gradients and stored energies (Ferry, (2005)). Also the microstructure presents a morphological texture where the grains are lengthened along the wire drawing axis Schindler et al., (2006); Schindler et al., (2009); Zidani et al., (2010).

Microstructure changes occurring during wire drawing can result in a record strength comparable with that of quenched steel Zelin (2002). Skolyszewski et al., (1996) investigated the mechanical properties variation in drawn wires of high-alloy steel and special alloys. The optimum ranges of deformation were determined; the influence of the distribution of partial reduction of area in the multi-stager drawing and distressing on the distribution of longitudinal stresses was investigated. The non-uniformity of properties on the cross-section of drawn bars was found to depend individually on the grade of the drawn bars.

The influence of back tension during wire drawing process was also considered in Skolyszewski and Packo, (1998). An attempt was made at finding the relationship between the critical back tension value and the mechanical properties of a material including optimization of the fine wire multi-stage slip drawing process and variations of the back tension value in successive deformation stages as well as the measurements of the drawing force, metal pressure on the die and back tension.

Effects of cold work on the properties of polycrystalline structures have been studied extensively by; Bosson and Driver (2000); Godfrey et al., (2001); Zaeffereret al., (2003); Ganapathysubramanian and Zabaras, (2004); Prasad et al., (2005); Dománková et al., (2007); Huda (2009); Pawlak and Krztoń (2009); Schindler et al., (2009); Raji and Oluwole (2011a)). A polycrystalline aggregate is a system composed of grains, grain boundaries, triple lines and quadruple junctions. The system forms a topological network with a specific number of elements Barrales-Mora et al., (2008).

When a metal is cold drawn, the microstructure presents a morphological texture where the grains are lengthened along the wire drawing axis Zidani et al., (2010), Schindler et al., (2006). 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 and a heat treatment procedure known as annealing is usually used to modify these defects and improve the mechanical properties of the 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. The modifications of the material during annealing occur in three stages known as recrystallization processes, according to temperature or time. These are; recovery, recrystallization and grain growth.

This paper discusses the influence of full annealing on the mechanical properties of plain nails which are manufactured by cold drawing of low carbon steel. The paper tends to expose the relationships between the mechanical properties of the nail and the degree of cold deformation when the nails are annealed at temperature above the austenitising temperature which ensures that all the ferrite in the material is transformed into austenite.

2.0 EXPERIMENTAL PROCEDURE

The material used for this study was a commercially available low carbon steel wire rod with the chemical composition in wt. % as tabulated in Table 1 obtained from Nigeria Wire Industry Limited, Ikeja. The steel was cold drawn in a series of drawing dies reducing the wire diameter from 5.5 mm to 5 mm, 4 mm, 3.3 mm, and 3 mm, respectively. These dimensions represents 20%, 25%, 40 % and 50% degree of deformation for the low carbon steel wire rods. 100 samples of the material were prepared for the experiment. 50 samples of the wires cut to 50 mm lengths were annealed in a Muffle furnace at 900 deg. C for 60 min soaking time and cooled in the furnace to temperature of 27 deg. C.

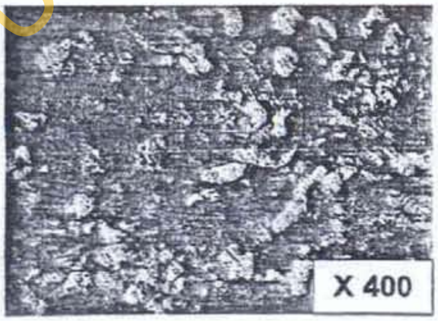
Table 1: Chemical composition of the as-received steel wire material used (% wt).

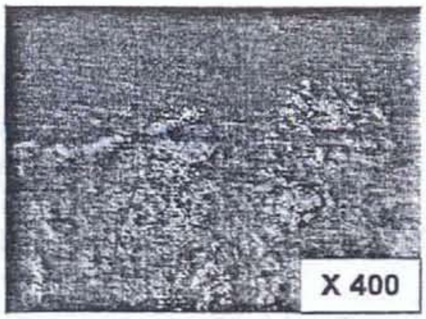
Element	C	Si	Mn	P	Fe
%	0.12	0.18	0.14	0.7	98.86

The Samples cut from the annealed wire were taken through a grinding process using silicon carbide paper, 240, 320, 400, and 600 grit and polished initially at 1μm and finally at 0.5μm using emery cloth and silicon carbide solution and etched with 2%-natal. Optical microscope (OM) with image capturing device was used to observe the microstructure of both the cold drawn and the annealed specimens. The planimetric procedure for the grain counting method was used to measure the mean grain size from the obtained micrographs as described in Raji and Oluwole (2011b). The samples were also subjected to tensile tests on a universal testing machine Instron 3369 with a load capacity of 50kN to obtain the strength-ductility properties of the samples at the different soaking time. The samples were also tested for impact toughness and hardness with increasing degree of cold deformation as described in Raji and Oluwole (2011a).

3.0 RESULTS AND DISCUSSIO

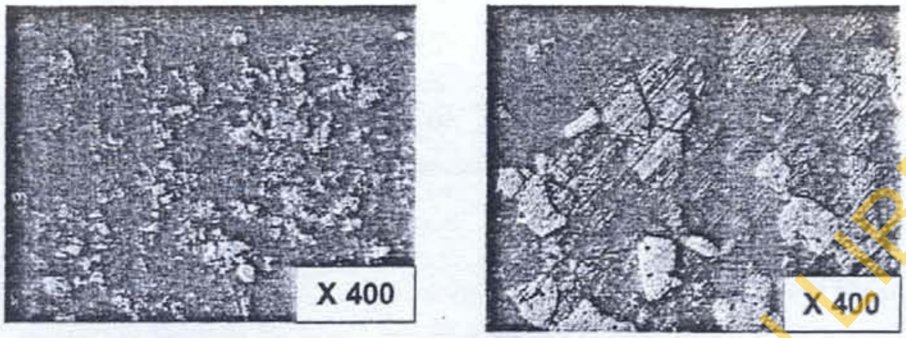
Annealing at 900^{0}C for 1hr led to recrystallization into a very coarse grained microstructure with increasing grain size as the degree of cold drawn deformation increases as observed in **Figures 1b-4b.** The microstructures present complete recrystallization with equiaxial grains having 103.25μm, 167.31 μm, and 196.67 μm average diameters for the 25%, 40% and 55% annealed cold-drawn steel respectively. The recrystallized grains at these degrees of deformation are fairly clean, largely free of defect and are equiaxial. However some nucleating grains are observed in the microstructure at 25% degree of deformation indicating that the recrystallization process at this degree of deformation is inhomogeneous involving simultaneous nucleation and grain growth.





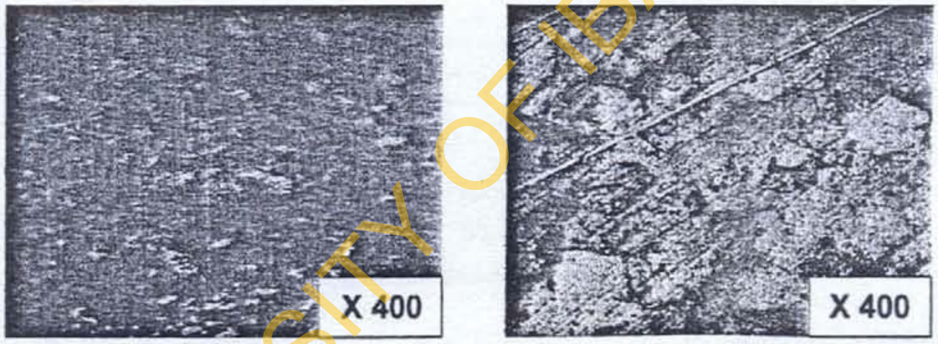
(a) (b)

Figure 1: Optical microscopy of longitudinal section of the samples etched with 2% nital: a) Cold drawn 20% diameter reduction; b) after 20% cold reduction and annealing in a muffle furnace at 900°C for 1 hr



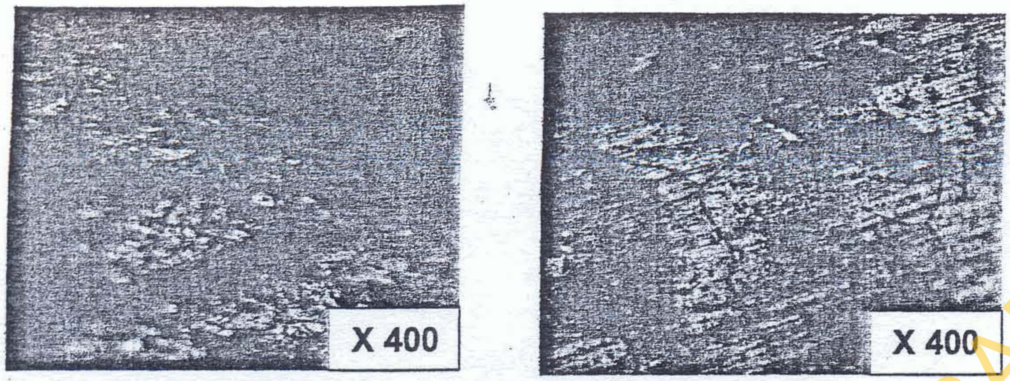
(a) (b)

Figure 2: Optical microscopy of longitudinal section of the samples etched with 2% nital: a) Cold drawn 25% diameter reduction; b) after 25% cold reduction and annealing in a muffle furnace at 900°C for 1 hr



(a) (b)

Figure 3: Optical microscopy of longitudinal section of the samples etched with 2% nital: a) Cold drawn 40% diameter reduction; b) after 40% cold reduction and annealing in a muffle furnace at 900°C for 1 hr



(a) (b)

Figure 4: Optical microscopy of longitudinal section of the samples etched with 2% nital: a) Cold drawn 55% diameter reduction; b) after 55% cold reduction and annealing in a muffle furnace at 900°C for 1 hr

At 20% degree of deformation the annealed samples show partially recrystallized microstructures. The deformed regions still contains some form of deformation and the formation of large quantity of nucleating grains. This implies that at this level of deformation, longer soaking time is necessary for complete recrystallization. Soaking time of 1 hr at 20 % cold-drawing only influenced recovery process which involves the annihilation of excess dislocations. The grain size of the steel increases as the degree of cold reduction increases for the annealed steel as shown in **Table 2**; indicating that grain growth of the recrystallized grain had taken place. The grain growth phenomena are evident from the grain boundary bulging observed in the structure at 25% degree of deformation showing that normal grain growth had taken place.

Table 2: Degree of Cold-drawn deformation and mechanical properties-grain size relationship of annealed Plain nails.

Cold drawn low carbon steel annealed at 900 deg. C soaked for 1 hr.							
% Cold drawn deformation	ASTM Grain size no.	Ave. Grain size dia. (□ m)	Tensile strength (N/mm^2)	Yield strength (N/mm^2)	Modulus of Impact toughness	Ductility	Brinnel Hardness (BHN)
20	NA	NA	900.94	468.41	14	0.40	477
25	3.57	103.25	472.26	246.93	7	0.38	383
40	2.22	167.31	330.84	185.33	3	0.28	354
55	1.75	196.67	215.17	130.37	1.7	0.21	285

From the data in **Table 2** it shows that the mechanical properties of the steel reduced as the degree of cold deformation increased. The yield strength property obtained for the annealed plain nails at the different degree of cold deformation as shown in **Figure 5** reduced with increasing degree of cold drawing an indication of reduction in ductility of the steel as evident in the result.

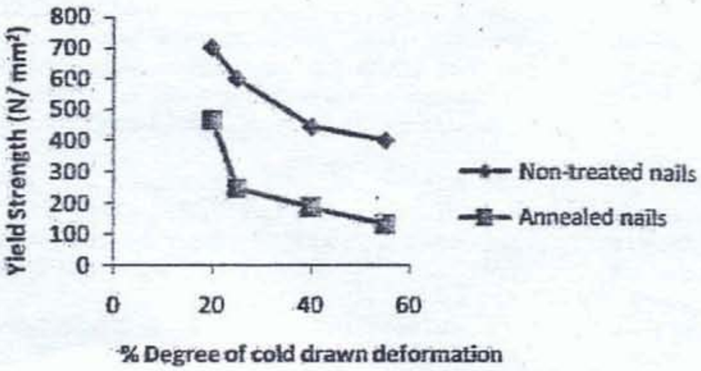


Figure 5: Influence of cold drawing deformation on the yield strength of non-treated and annealed nails

Similar trend is observed for the tensile strength as shown in **Figure 6**, and toughness of the material as shown in **Figure 7**. The figures also show the comparison of these properties with the non-treated nails. This implies that increasing the properties of the nail in service may not be achieved by the full annealing at temperature above the austenite range for a soaking time of 1 hour.

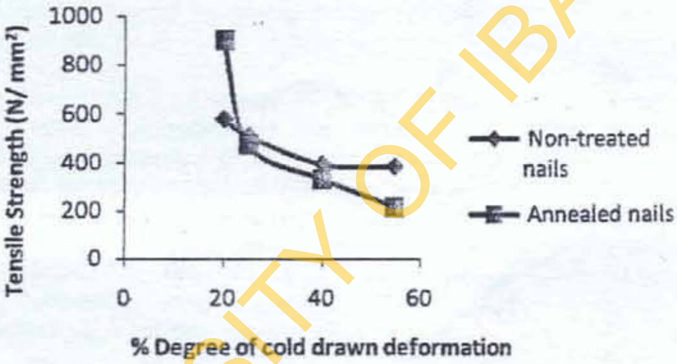


Figure 6: Influence of cold drawing deformation on the Tensile strength of non-treated and annealed nails

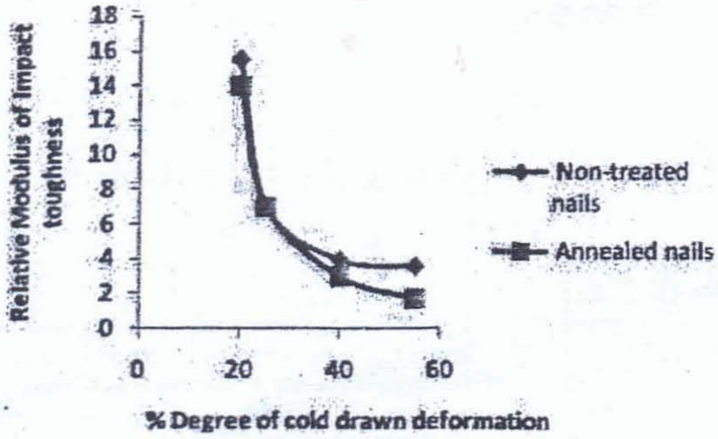


Figure 7: Influence of cold drawing deformation on toughness of non-treated and annealed nails

CONCLUSION

The influence of full annealing of low carbon steel has been studied relating the yield strength, tensile strength and toughness properties of the steel to its microstructure when annealed at $900^{O}C$ for 1 hour soaking time. The full annealing tends to reduce these properties for the low carbon steel as applicable for nail manufacture. The microstructure formation shows that soaking time of 1 hr at 20 % cold-drawing only influenced recovery process which involves the annihilation of excess dislocations. It is observed that the nucleation and growth rate at higher cold-drawn deformation of 25% - 55% are higher for the 1 hour soaking time compared to the 20% cold drawn deformation. Annealing at $900^{O}C$ for 1 hour full annealing therefore recrystallized a higher proportion of the steel at higher degree of cold-drawn deformation. It is also observed that for the annealed steel, the grain size of the steel increases as the degree of cold reduction increases for annealing time of 1 hour. Grain coarsening led to increased grain size as the degree of cold-deformation increases at the same 1 hr full annealing time.

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