ASSET Series B (2007) 6 (1): 12-20

ASSET
An
International
Journal

EFFECTS OF PROCESS ANNEALING ON MECHANICAL PROPERTIES OF STRAIN HARDENED (NS 34 LC) COILED WIRE

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ABSTRACT

The effects of annealing on the mechanical properties of strain hardened coiled-rolled wire of low carbon steel, which is used for manufacturing barbed wire, office pins, nails and fencing were investigated in this paper. The as-received coiled-rolled wire was strain-hardened by drawing it through drafts of 30.56, 55.56, 75.00 and 88.89%, respectively. This was followed by process annealing at 400, 500 and 650°C. The tensile strength, yield stress, hardness, percentage reduction in area and percentage elongation of the annealed specimens were evaluated and compared with values for commercial specimens. The results obtained showed that NS 34 LC rolled coiled wire attains its full hardness or full brittleness at 88.89% strain hardening. It was observed that for optimal mechanical properties of cold worked coiled wire of the low carbon steel, the material should not be strain hardened beyond the drawing of 75% draft and should be critically annealed at 650°C for soaking time of 15 minutes before further deformation.

Keywords: annealing coiled wire, deformation, mechanical properties and strain-hardening.

INTRODUCTION

Generally, deformation of metals occurs principally by the motion of existing dislocation and creation of many additional dislocations (Guy and Hren 1994; Zerilli and Armstrong, 1987). As the dislocation density increases with the cold deformation, it becomes more difficult for the dislocation to move through the existing mass of dislocation, hence the metal work or strain hardens with increased cold deformation (Fonteyn and Pitsi, 1990; Nestorovic and Tancic, 2002; Callister, 2007).

Recent research results show that the magnitude of hardening of cold-worked metal depends on the area reduction, temperature and strain rate associated with the processing, and on the way the strain is imposed on the metal (Peeters et al., 2001; Rauch et al., 2002). Keeping all other variables constant, the work hardening of a metal submitted to a sequential straining under varying directions or of different natures is different from that resulting from monotonic straining. Changes in the way the material is deformed can alter the hardening rates and influences in various ways the mechanical behavior of annealed drawn metal wires (Cetlin et al., 1998; Correa et al., 2000).

According to Kouzeli and Mortensen (2002), the size parameters characteristic of a material's microstructure can exert a strong influence on its mechanical properties, most of these size effects come about because of the constraint to which a particular deformation mechanism is being subjected. Lattice dislocations are forced by the microstructural constraint to bow out or pile up, and their movement requires an external stress dependent on a microstructural parameter (Mimura et al., 1997; Majta and Zurek; 2003; Majta et al., 2005).

The results of the effect of strain hardening on coiled wire during cold drawing require a decrease in reduction rate, and the maximum reduction of coiled wire prior to process annealing needs to be established as a factor of safety during design for plastic deformation. Therefore, the objective of this research work is to study experimentally, the effects of process annealing on the mechanical properties of strain-hardened coiled wire during plastic deformation using Nigerian Wiring Industries Limited (NIWIL) as a case study. The result should be of immense benefit to all the users and manufacturing industries most especially in Nigeria.

MATERIAL METHODS

Basic Theory

The continuing plastic deformation of low carbon steel, which increases its hardness as its crystal grains become distorted and fragmented, is known as work/strain hardening (Guy and Hren, 1994; Rollason, 1996). The strain hardening relationship of coiled wire can be measured by the changed in its ultimate tensile strength (UTS) as against the percentage reduction in cross sectional area.

$$\%\ \text{Reduction in cross-sectional area} = \frac{A_o - A}{A_o} \times 100\% \qquad \text{(1)}$$

where, A_0 is initial area in m^2; and A is the value of area at required reduction in m^2. The hardness number is a function of both the magnitude of the load and the diameter of the resulting indentation (Eq. 2).

$$BHN = \frac{2P}{\pi D\left[D - \sqrt{\left(D^2 - d^2\right)}\right]} \qquad \text{(2)}$$

Materials

Six (6) mm diameter rolled coiled wire rod weighing 15kg were collected from (NIWIL) from the drawing shop. The ladle chemical composition and mechanical properties of the material are shown in Tables 1 and 2, respectively.

Table 1: Ladle chemical composition of the material

Ladle Chemical Composition	Percentage per weight (%)
Carbon (C)	0.06 – 0.12
Silicon (Si)	0.18 – 0.28
Manganese (Mn)	0.04 – 0.60

Table 2: Mechanical properties of the material

Mechanical Properties	Values
Ultimate Tensile Strength	305 – 404 (N/mm^2)
Yield strength	220 N/mm^2 (minimum)
Percentage Elongation	40% (minimum)

Experimental Procedure

Approximately 150 mm gauge length test pieces were used for tensile tests (NSO, 1973) and the gauge marks were 4d apart (where d is the diameter of the wire under test (ASTM,1990). The tensile strength/hardness conversion was used to find their hardness number (Kalpakjiam, 1989). The test pieces were strain hardened by wire drawing from 6 mm diameter. The test pieces were drawn to 30.56, 55.56, 75.00 and 88.89%, respectively, by strain hardening.

The tensile tests were carried on the specimens using a universal testing machine (Hounsfield Tensometer). The tensile strength, yield point, yield strength, percentage elongation and percentage reduction in area were read from the digital display attached to the machine. Thereafter, process annealing was performed on the test pieces in a metallurgical heating furnace. Three temperatures 400, 500 and 650^{0}C were used to anneal the specimens that were strain hardened to 30.56, 55.56, 75.00 and 88.89% drafts. The test pieces were heated at the furnace rate and soaked for 15 minutes at the attainment of the required temperatures. Tensile tests were then carried out on the annealed test pieces.

RESULTS AND DISCUSSION

Effect of Strain Hardening on the Mechanical Properties of (NS 34 LC) Coiled Wire

The graphs of mechanical properties against strain hardening are shown in Figs. 1 and 2. The tensile strength of NS 34 LC as rolled was found to be 369 N/mm^2 which on strain hardening to 2 mm was increased to 922 N/mm^2. This is an increase of 150% over a range of 2 mm strain hardening. The initial hardness value by tensile strength/hardness conversion (UTS = 3.5 BHN; UTS in N/mm^2) was 105.43 N/mm^2 and was increased by strain hardening to 263.42 N/mm^2. The ratio of reduction increased from initial ration of 2.38:1 to final ratio of 16:1.

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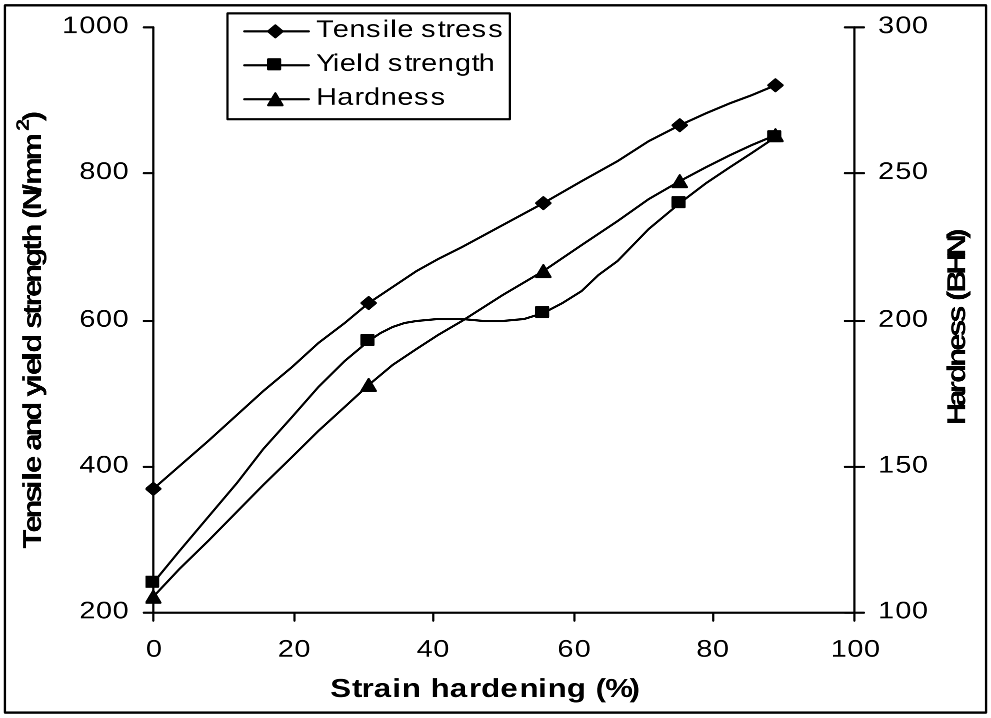

Fig. 1: Effects of strain hardening on the hardness and Strength of NS 34 LC Coiled Wire

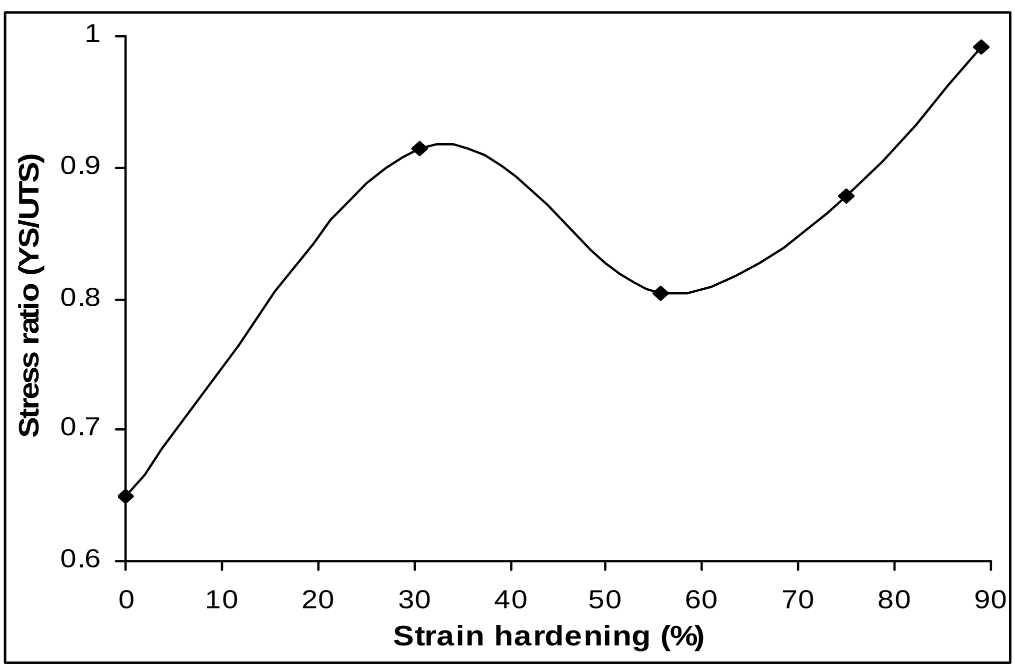

Fig. 2: Effect of strain hardening on the stress ratio (YS/UTS) of NS 34 LC Coiled Wire

From Fig. 1, the curves of the ultimate tensile strength and yield strength are observed to intercept at 88.89% strain hardening. A similar observation for the ratio of yield strength and ultimate tensile strength as shown in Fig. 2, which is quite significant. Thus NS 34 LC rolled coiled wire has attained its full hardness or full brittleness at 88.89% strain hardening.

Effects of Sub-Critical Annealing on the Mechanical Properties of NS 34 LC

The curves of mechanical properties against process annealing (or sub critical annealing) temperatures for NS 34 LC strain hardened to 5 mm (30.56% strain hardening) are shown in Figs. 3 and 4. The curves for 4, 3 and 2 mm (55.56, 75.00 and 88.89%) strain hardening follows the same trend. It can be seen from the Figures that process annealing influences the mechanical properties of NS 34 LC coiled wire; the tensile strength and hardness were found to reduce as the annealing temperatures increased (Fig. 3). Also, the elongation and reduction in area were found to increase with the annealing temperature (Fig. 4).

The Effects of Strain Hardening on Strain Hardening Exponents

The Hollomon Equation (Cetlin et al., 1998) ($\sigma = K\sigma^n$ or $\log \sigma = \log K + n \log \sigma$) was applied and the strain hardened exponent for each strain hardened material was determined. From Fig. 5, it was observed that the strain hardening exponent, n, decreases as strain hardening increases; where, n is an index of drawability, which shows that the strain hardening has an inverse relationship with drawability. The reduction drawability of NS 34 LC became more pronounced as from 75.00% strain hardened.

Effect of Process Annealing on Strain Hardened Exponents

The effect of process annealing on strain hardened exponents of NS 34 LC rolled coiled wire is shown in Fig. 6. The strain hardening exponents of NS 34 LC ranges between 0 and 0.60 for situations before strain hardening, after strain hardening and after annealing of the strain hardened coiled wire. Since strain hardening exponents, n, decreases as strain hardening decreases, n is therefore an index of drawability. It was observed that at 75% strain hardening, the drawability (value of n) of the rolled coiled wire was very low at annealing temperatures of 400 – 500^0C (Fig. 6), but at the same 75% strain hardening, the steel has superior drawability to 55.56% and 30.56% strain hardening at the annealing temperatures of 550 to 600^0C. At higher annealing temperatures the drawability is as good as that of 88.89% strain hardening.

The need for process anneal cycle can be met by interpolating between charts showing the effects of process annealing on various percentages of strain hardening of NS 34 LC rolled coiled wires. The annealing temperature required can be determined having known the percentage of strain hardening of the materials.

ISSN 1595—9694

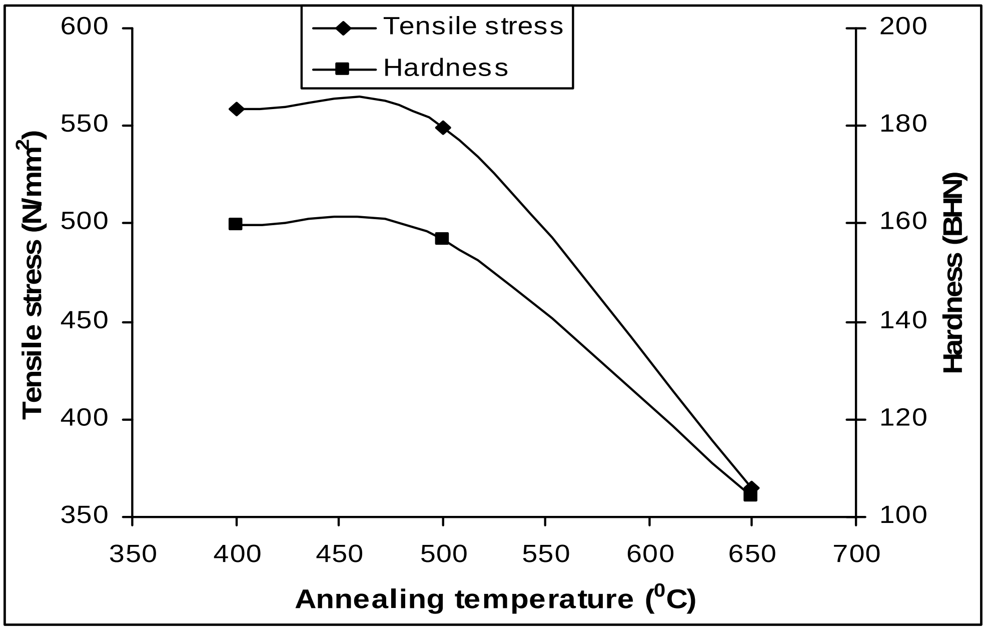

Fig. 3: Tensile stress and hardness versus annealing temperature

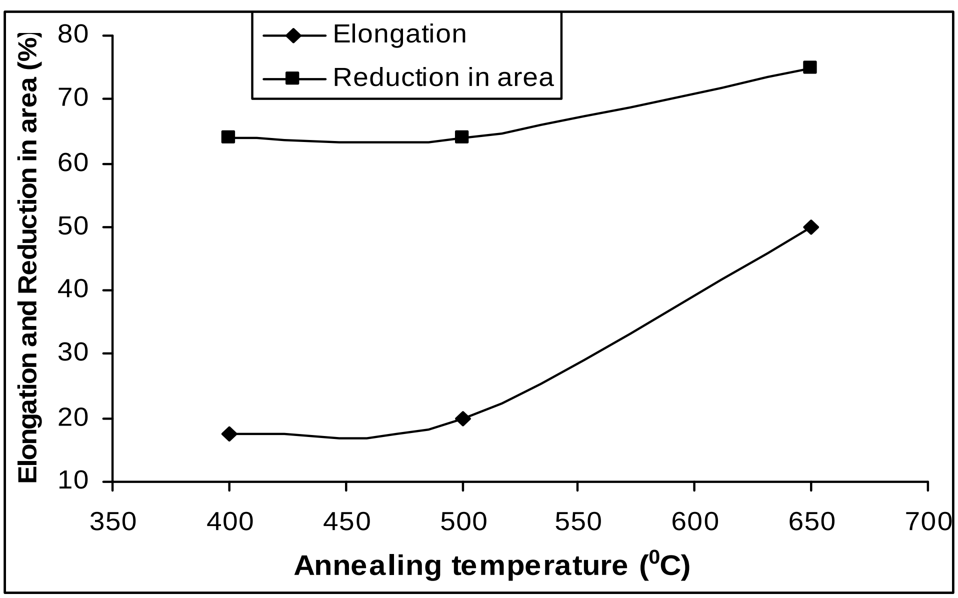

Fig. 4: Percentages of elongation and reduction in area versus annealing temperature

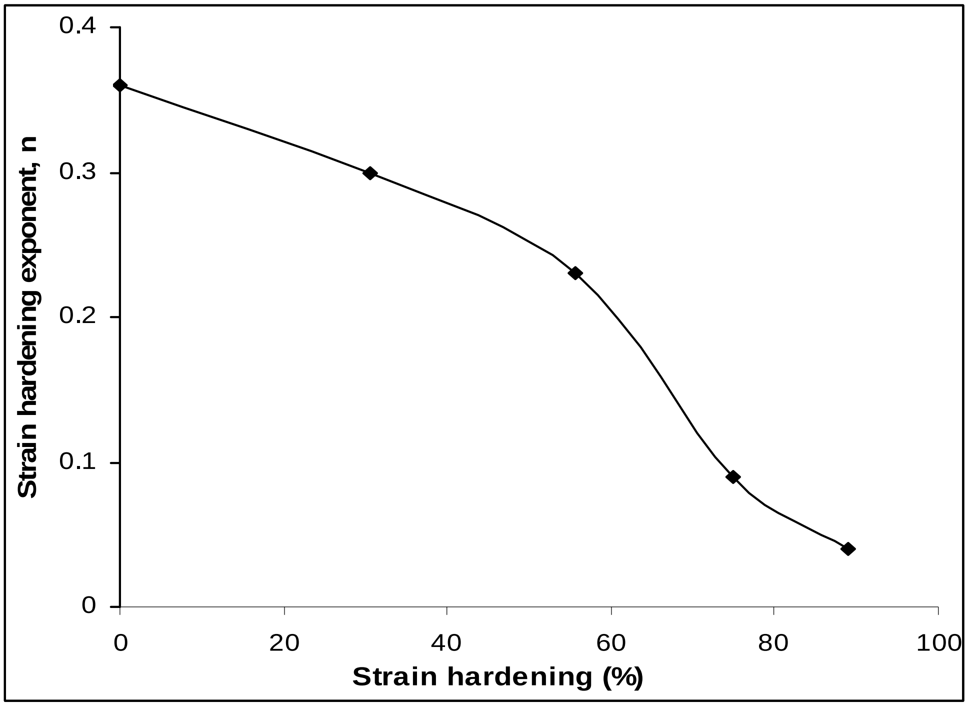

Fig. 5: Effects of strain hardening on strain hardening exponents, n, of NS 34 LC

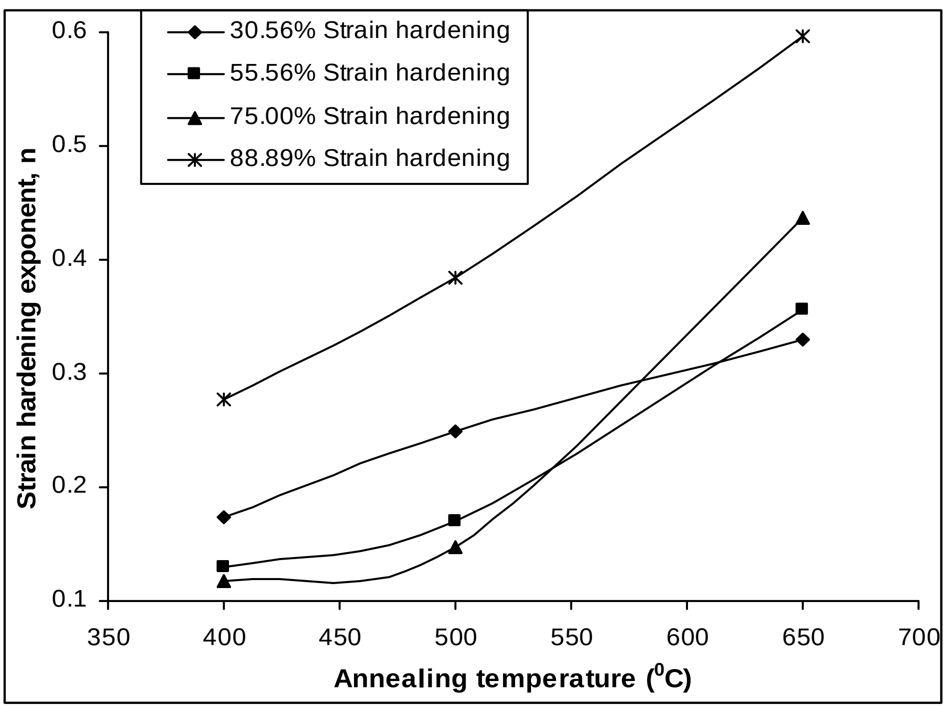

Fig. 6: Effects of subcritical annealing on the strain hardening exponents, n, of NS 34 LC coiled wire

CONCLUSION

The effects of annealing on the mechanical properties of strain hardened NS 34 LC rolled coiled wire were investigated. The material was strain-hardened by drawing it through drafts of 30.56, 55.56, 75.00 and 88.89%, respectively. This was followed by process annealing at 400, 500 and 650^{0}C. The tensile strength, yield stress, hardness, percentage reduction in area and percentage elongation of the annealed specimens were evaluated. The results obtained showed that the strain hardening exponents of NS 34 LC ranges between 0 and 0.60 for situations before strain hardening, after strain hardening and after annealing of the strain hardened coiled wire. NS 34 LC rolled coiled wire attains its full hardness or full brittleness at 88.89% strain hardening and (as a factor of safety against fracture) the material should not be strain hardened beyond the drawing of 75% draft. Also, a 650^{0}C annealing temperature and a soaking time of 15 minutes are recommended to remove the effect of previous strain hardening (cold working on NS 34 LC). The data provided in Figures 1 to 6 can be used as a guide in processing this grade of steel wire for the final product to meet the specifications of Standard Organization of Nigeria (SON).

ACKNOWLEDGEMENT

The authors are grateful to Nigerian Wire Industries Limited, at NIWIL Road, Ogba Ikeja for providing the wire samples and for access to equipment used for this work.

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