# EFFECTS OF SUB-CRITICAL ANNEALING ON THE MECHANICAL PROPERTIES OF STRAINED-HARDENED NST 37-2

BY

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## ABSTRACT

This work reports the result of the thermo-mechanical investigations carried out on strain-hardened NST 37-2 - a Nigerian low carbon steel that has a wide industrial applications; the objective being to improve the drawability of this grade of steel.

NST 37=2 is strain-hardened by wire-drawing from 6mm diameter rolled product to 5mm (30.56% reduction), 4mm (55.56% reduction), 3mm (75% reduction), and 2mm (88.89% reduction). Mechanical properties-yield strength, ultimate tensile strength, hardness, per cent elongation and per cent reduction in area are determined on the test pieces before and after the wire drawing (strain-hardening) operations. This is followed by sub-critical annealing at annealing temperatures of 500°C and 650°C. Microstructural investigations are carried on the strain-hardened and annealed test pieces.

For optimum drawability NST 37-2 should not be strain-hardened beyond 75% reduction and the strain-hardened steel should be sub-critically annealed at 650°C annealing temperature for 15 minutes.

**KEYWORDS:** Strain-hardening,sub-critical annealing, mechanical test, drawability.

## INTRODUCTION

During cold-working, dislocations multiply and interact leading to an increase in the strength of the metal. Thus cold-working or strain-hardening is one of the most important methods for strengthening of some metals particularly steel. Although strain-hardening mechanism is not yet fully understood, the application of the existing knowledge on strain-hardening in engineering practice is enormous.

The ability of a metal to be drawn depends significantly upon the type of the metal, the geometry of the piece and the nature of drawing operations. Drawability is an attribute that has no precise universal meaning. Since we are restricting our attention to wire-drawing in this work, the limit of drawability is associated with the onset of plastic instability at which the wire thins catastrophically and breaks. Thus drawability which is impeded by strain-hardening is very important in engineering practice.

Professor Dr. R. Wusatowski in his work titled, "Recommendation For Selection of Wire-rod for nail Manufacturing," found out that as a result of the effects of strain-hardening on the materials for nail manufacturing the wire drawing practice requires a decrease in reduction rate when the total reduction rate (last annealing) exceeds 65 - 75%.

In the same work, he noticed that the experience of nail manufacturing teaches also that the excessive wire deformation rate causes trouble during headforming of nails. "The strain-hardening relationship of the steel grade to be used for nail manufacturing will bring the solution" and has found this relationship by the measurement of the ultimate tensile strength (UTS) changes against the deformation of as-drawn wires. Also the relationship between the yield strength (Y.P) and deformation rate (R) was used.

$Y.P. = AR^b \Rightarrow \text{Log } Y.P = \log A + b \log R.$
where Y.P = yield strength
R = reduction rate (%)
A, b = constants

He was able to use the two relationships to determine ratios for all cases before cold deformation and during cold deformation and thus concluded that

$\frac{YP}{UTS}$ approaches 1 ($\frac{YP}{UTS} \rightarrow 1$) the brittleness of the material increases while ductility or drawability decreases.

From the ratio he was able to recommend the maximum and minimum deformation that should be

given any type of nail with specification from Standard Organization of Nigeria (SON) for wire nails. This present work is thus an extension of the previous work done on strain-hardening of steel and our focus is on the Nigerian Low carbon steel, NST 37-2; the objective is to improve the drawability of this grade of steel. NST 37-2 has an average ultimate strength (UTS) of 37 kg/m$^2$ (370 N/mm$^2$) which has its billets further processed by hot rolling in the rolling companies. This becomes the raw materials for wire-drawing mills. At the wire drawing mill the wire rod is cold-drawn (strain-hardened) to enhance the mechanical strengths of the smaller sizes that will be suitable for production of sections such as angles, channels, flatbars, and tee. It is also suitable for medium strength nuts, bolts, machine screws and nail manufacturing. It has been observed that during further processing of these wires by the nail manufacturing industries, that most of the wires had undergone excessive strain-hardening and so they break such that the initial set up for production has to be re-organized. This invariably causes product, energy and time wastage. Hence maximum per centage of cold-work (strain-hardening) for NST 37-2 prior to sub-critical annealing need to be established as a factor of safety during design for plastic deformation.

## 2. EXPERIMENTAL DETAILS

### 2.0 Materials

6mm diameter wire rolled products of NST 37-2 weighing 13.5kg were collected from Jos Steel Rolling Mill for wire drawing at Highland Steel and Allied Industries in Jos. The designations, ladle chemical composition and mechanical properties of the material is shown in Table 1.

### 2.1 Experimental Procedure

#### 2.1.1 Tensile Test

The test pieces were cut from NST 37-2 6mm wire rolled product and from those strain-hardened by wire-drawing to 30.56%, 55.56%, 75% and 88.89%. For mechanical test (tensile), wire length up to 40cm each were used on OLSENTINUS universal testing machine of 300 KN force capacity for the determination of the mechanical properties.[2] The gauge length used was 150mm while[3] the gauge marks along the gauge length were 4d (where d is the diameter of the wire under test).

The hardness/ultimate tensile strength (UTS) relationship[4] was used for the evaluation of hardness numbers:

UTS = 3.5 (BHN) (BHN is Brinnel Hard-

The strain-hardening exponent, n , a measure of drawability was determined from the general Holloman equation[5] for tensile plastic region: $\sigma = K \delta^n$

$\sigma$ = true stress
$\delta$ = true strain
K = strength co-efficient
n = strain-hardening coefficient

Taking Log of both sides of holloman equation we have:

$$\text{Log } \sigma = \text{Log } k + n \log \delta$$

plot of log $\sigma$ against log $\delta$ gives a straight line graph with n as the slope and log k as the intercept.

#### 2.1.2 Initial test before strain-hardening

The test piece for the mechanical test (tensile) of the as-rolled product was installed into the testing machine after putting the gagemarks and gauge length and was pulled to fracture. The tensile strength, elongation, per centage reduction in area and hardness were calculated.

#### 2.1.3 Tensile test after strain-hardening

Wire drawing process was employed for strain-hardening the 6mm diameter wire rolled product to 5mm (30.56% reduction), 4mm (55.56% reduction), 3mm (75% reduction), and 2mm (88.89% reduction). The tensile test was conducted as in section 2.1.2 on each of the strain hardened materials and the necessary values were obtained.

#### 2.1.4 Sub-critical Annealing and Tensile Test

A metallurgical furnace of 1000° capacity was used to anneal the strain-hardened materials to 400°C, 500°C and 650°C. They were heated at the furnace rate and soaked for 15 minutes at the attainment of the required temperature. They were then cooled in the furnace to room temperature.

Tensile tests following the same procedure as before was then conducted on these materials to determine the effect of the sub-critical annealing on the drawability of the strain-hardened materials.

#### 2.1.5 Metallography

The test piece of NST 37-2 as-rolled for microstructural investigation was mounted, ground, polished and etched. The microstructure was examined through the optical microscope and then snapped to give the micrograph.

The pieces strain-hardened to 30.56% and 55.56% reduction were cut and prepared for micro-structural investigation to determine the effect of strain-hardening on the initial microstructure.

Fresh pieces strain-hardened to 30.56% and 55.56% reduction were annealed in the furnace to 500°C and 650°C and the microstructural investigation was carried out on them.

## 3.0 RESULTS AND DISCUSSIONS

### 3.1 The Effect of Strain-hardening on the Mechanical Properties of NST 37-2

Figures 1, and 2, 2(b) illustrate the effect of cold-drawing (strain-hardening),on the mechnical properties. While the tensile strength, yield strength and hardness increases the ductility (in terms of per centage elongation and per centage reduction in area) reduces. In figure 2(b) the ratio of the yield stress and the ultimate tensile strength approximates 1 at 90% strain-hardening.

### 3.2 Effect of Sub-critical Annealing on the Mechanical Properties of Strain-hardened NST 37-2

The curves of mechanical properties versus annealing temperature for NST 37-2 strain-hardened to 30.56%, 55.56%, 75% and 88.89% are shown in figures 3, 4, 5, 6, 7, 8, 9, and 10. It can be seen from the figures that the initial properties of NST 37-2 which changed during strain-hardening as observed in Section 3.1 are now being restored as the annealing temperature increases from 400°C to 650

### 3.3 Effect of Strain-hardening on the micro structure of NST 37-2

The photomicrographs shown in figures 13, 14, and 15 show the pearlite grains (black spots) in ferrite matrix (white background). Both pearlite and ferrite grains are elongated as the percentage strain-hardening increases from 30.56% to 55.56%.

### 3.4 Effect of Sub-critical Annealing on the Microstructure of Strain-hardened NST 37-2

Figures 16, 17, 18, and 19 show the effect of using two sub-critical annealing temperatures (500°C and 650°C) on the elongated microstructure of NST 37-2. As the temperature increases from 500°C to 650°C the number of pearlite in the ferrite matrix reduces which enhances the softening of the material as the annealing temperature increases.

### 3.5 Effect of Strain-hardening on the strain-hardening exponent,n

Strain hardening exponents n, which describes the drawability of NST 37-2 are illustrated by figure 11. It is observed that thisexponent or drawability decreases with strain-hardening.

### 3.6 Effect of sub-critical Annealing on the strain-hardened exponent of strain-hardened NST 37-2

High drawability is imparted to the strain-hardened NST 37-2 by sub-critical annealing and drawability of the strain-hardened steel increases as the annealing temperature increases. This is illustrated by figure 12. As the annealing temperature increases so is the strain-hardening exponent, n, and invariably the drawability of the material.

## 4. CONCLUSIONS

On the basis of the results of this investigation on the effects of sub-critical annealing on the mechanical properties of strain-hardened NST 37-2 the following conclusions are drawn:

1. The following mechanical changes occur during the strain-hardening of NST 37-2:
   - i) increased yield strength
   - ii) increased ultimate strength
   - iii) increased hardness
   - iv) decreased ductility

2. Strain-hardening exponents range between 0.03 and 0.60 for situation before strain-hardening, after strain-hardening and after sub-critical annealing.
3. The microstructure of the original NST 37-2 as-rolled products are distorted during strain-hardening.
4. The points of fracture can be predicted for NST 37-2 during strain-hardening by making use of the per cent reduction in area to calculate the final diameter that can be given the materials before strain-hardening, after strain-hardening and after annealing of the strain-hardened steel having known the initial diameter from which the initial cross-sectional area was found.
5. NST 37-2 attains full hardness and full brittleness (The ratio of $\frac{YP}{(UTS)}$ -----> 1 at 90% strain-hardening) state at 90% strain-hardening and so for a factor of safety should not be annealed to 650°C annealing temperature for 15 minutes before further deformation.

**ACKNOWLEDGEMENTS**

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2. Nigerian Standard Organization (NSO), Methods for Torsion and Tensile testing of steel wires. Federal Ministry of Industries, Lagos, Nigeria, 1973.

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4. Serope Kalpakjian, Manufacturing Engineering and Technology, Addison, Wesley Publishing Company, USA, 1989, p. 78.

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ABLE 1: DESIGNATION, LADLE CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF NST 37-2

NST - Nigerian Steel
37 - average ultimate tensile strength (UTS) = 37 kg/mm2 (i.e 370N/mm2)
2 - average percentage elongation (0.2 or 20%)

| Ladle chemical composition wt% | |
|---|---|
| Carbon = 0.12-0.17 | Ultimate tensile strength = 340-470(N/mm$^2$) |
| Silicon (sil) = 0.18-0.28 | Yield strength = 225 N/ mm$^2$ (minimum) |
| Manganese (Mn) = 0.04-0.60 (minimum) | Percentage elongation = 24% |

**DIGITAL IMPEDANCE RELAYING**

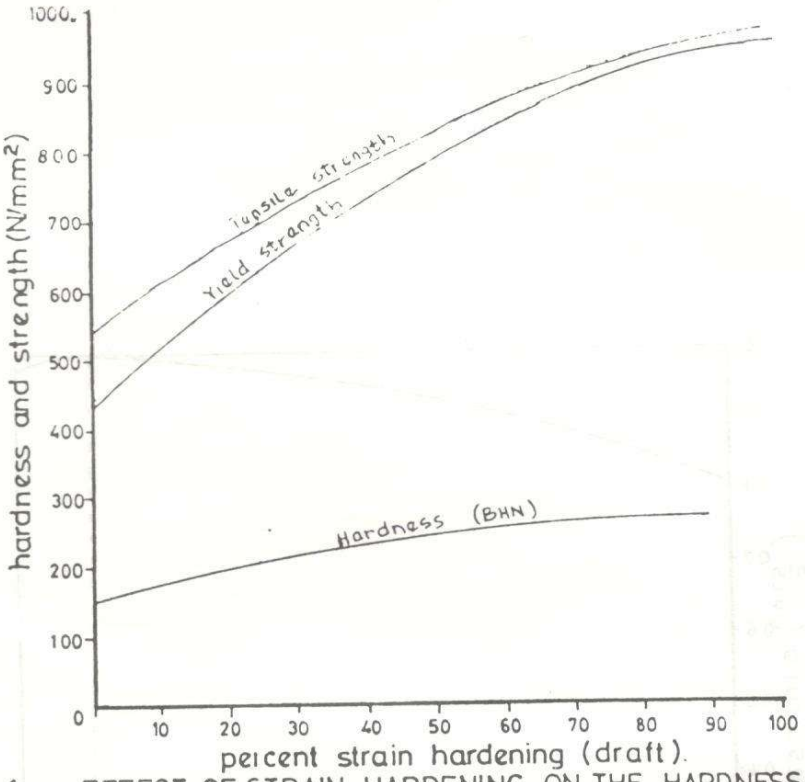



Fig. 1 EFFECT OF STRAIN HARDENING ON THE HARDNESS AND STRENGTH OF NST 37-2

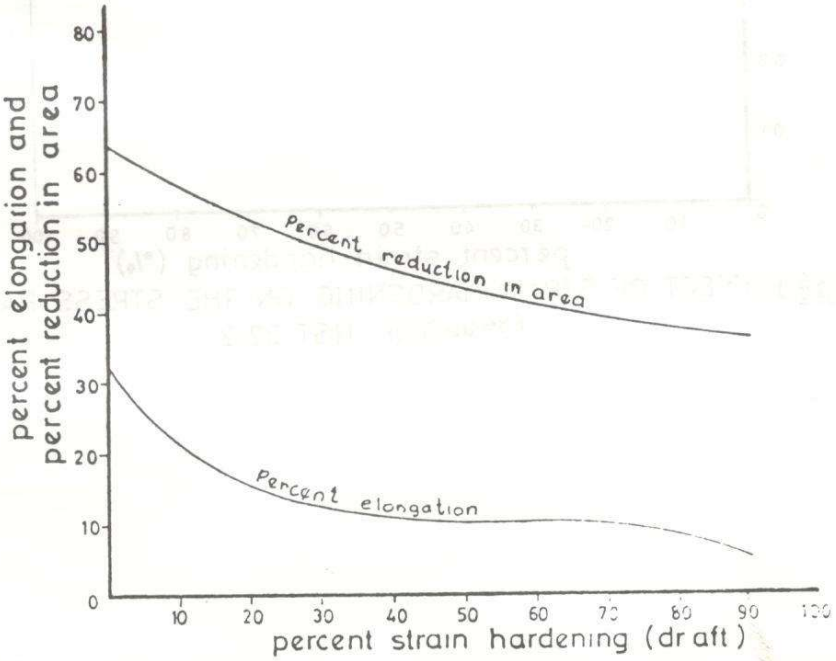



Fig 2 EFFECT OF STRAIN HARDENING ON DUCTILITY OF NST 37-2

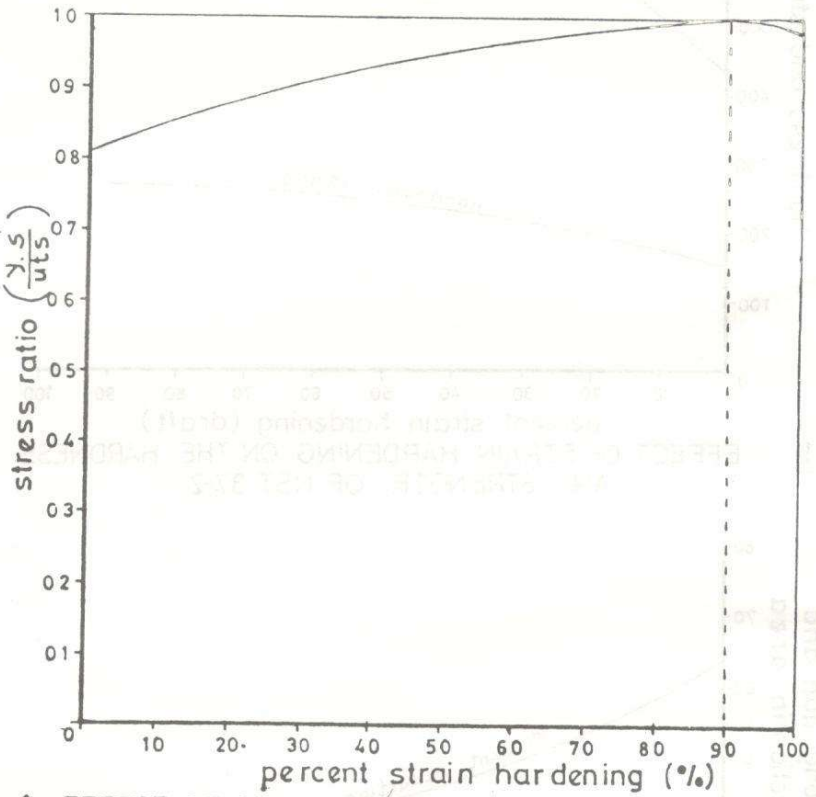



Fig. 2(b) EFFECT OF STRAIN HARDENING ON THE STRESS RATIO (ys/uts) OF NST 37-2

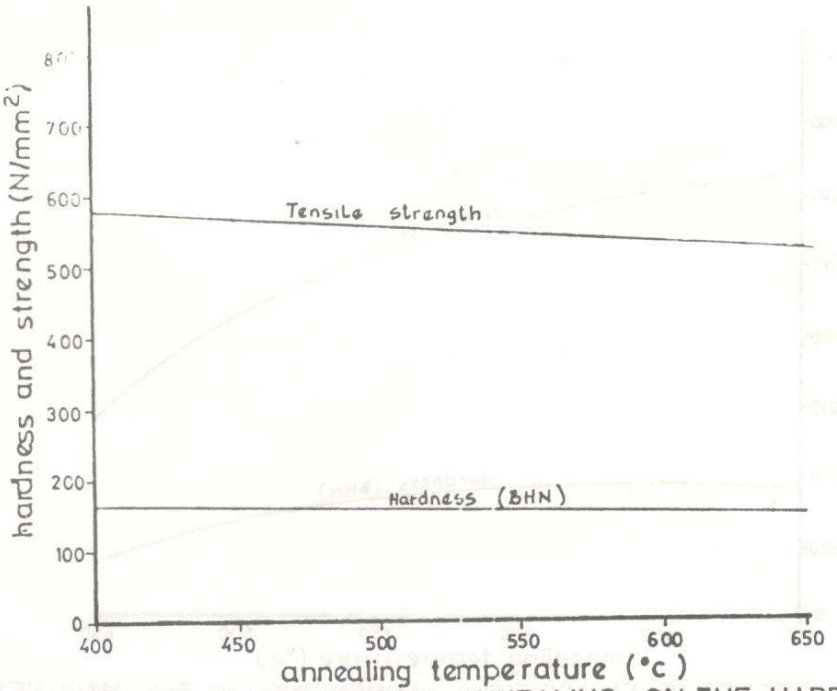



Fig. 3 EFFECT OF SUBCRITICAL ANNEALING ON THE HARDNESS AND STRENGTH OF NST 37-2 STRAIN HARDENED TO 30.56 %

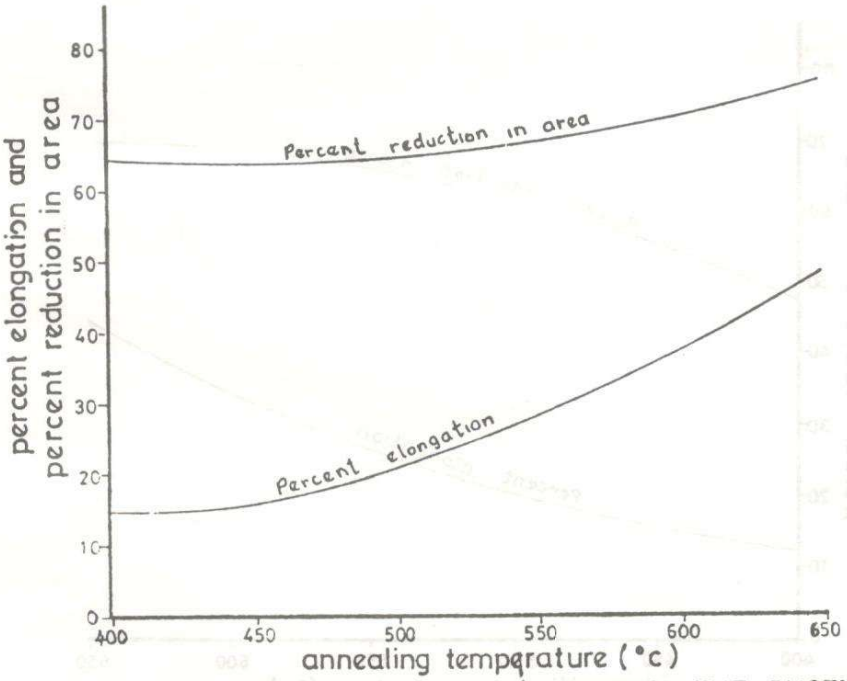



Fig. 4 EFFECT OF SUBCRITICAL ANNEALING ON THE DUCTILITY OF NST 37-2 STRAIN HARDENED TO 30.56 %

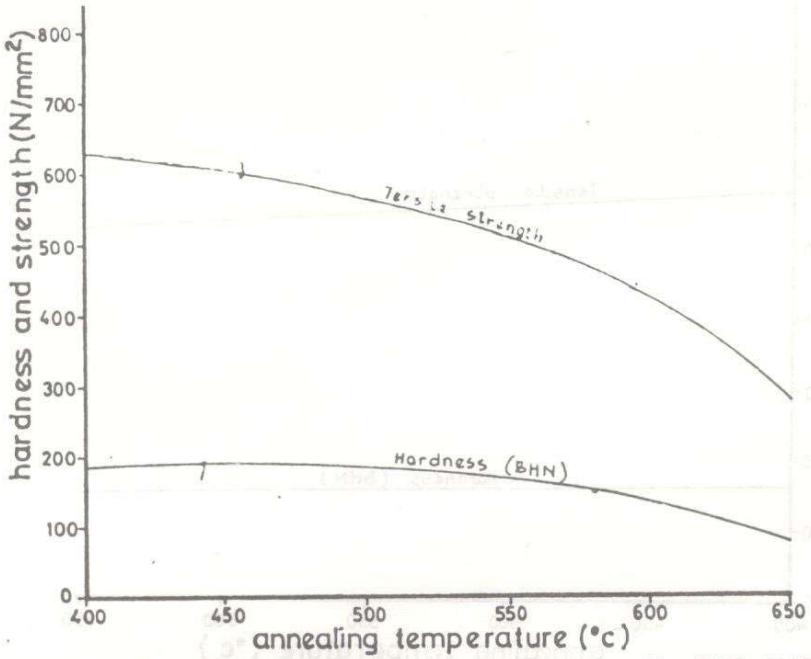



Fig. 5 EFFECT OF SUBCRITICAL ANNEALING ON THE HARDNESS AND STRENGTH OF NST 37-2 STRAIN HARDENED TO 55.56 %

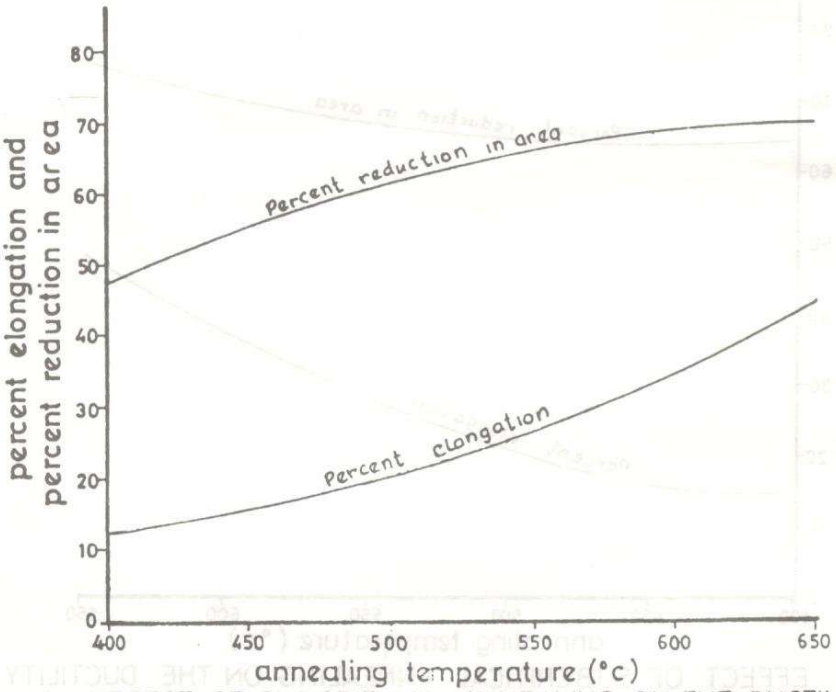



Fig. 6 EFFECT OF SUBCRITICAL ANNEALING ON THE DUCTILITY OF NST 37-2 STRAIN HARDENED TO 55.56 %

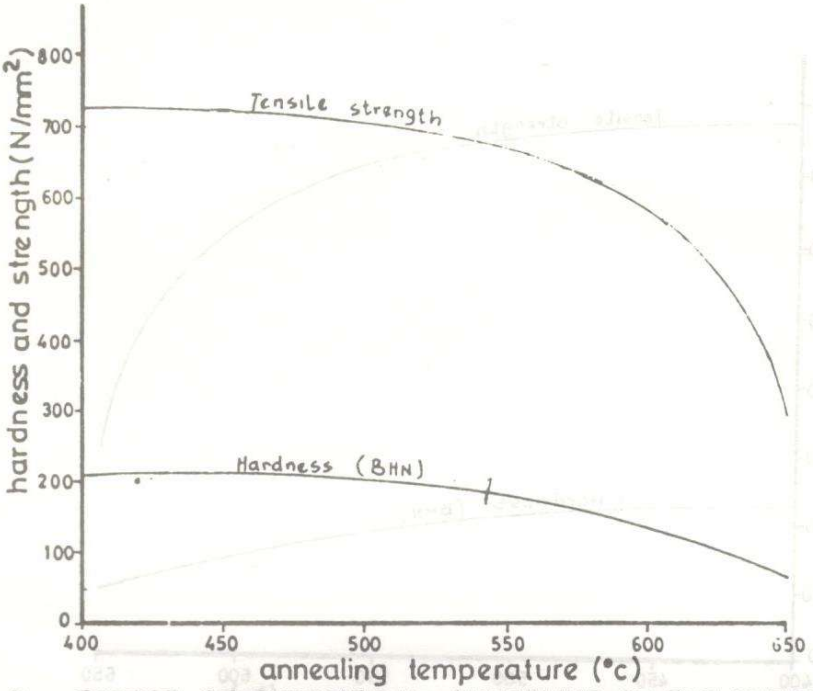



Fig. 7 EFFECT OF SUBCRITICAL ANNEALING ON THE HARDNESS AND STRENGTH OF NST 37-2 STRAIN HARDENED TO 75 %

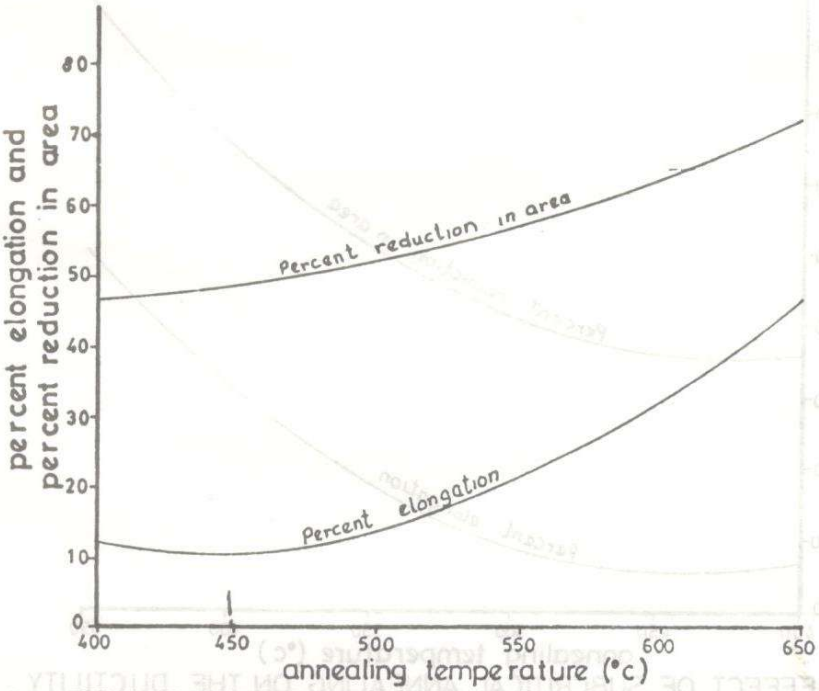



Fig. 8 EFFECT OF SUBCRITICAL ANNEALING ON THE DUCTILITY OF NST 37-2 STRAIN HARDENED TO 75 %

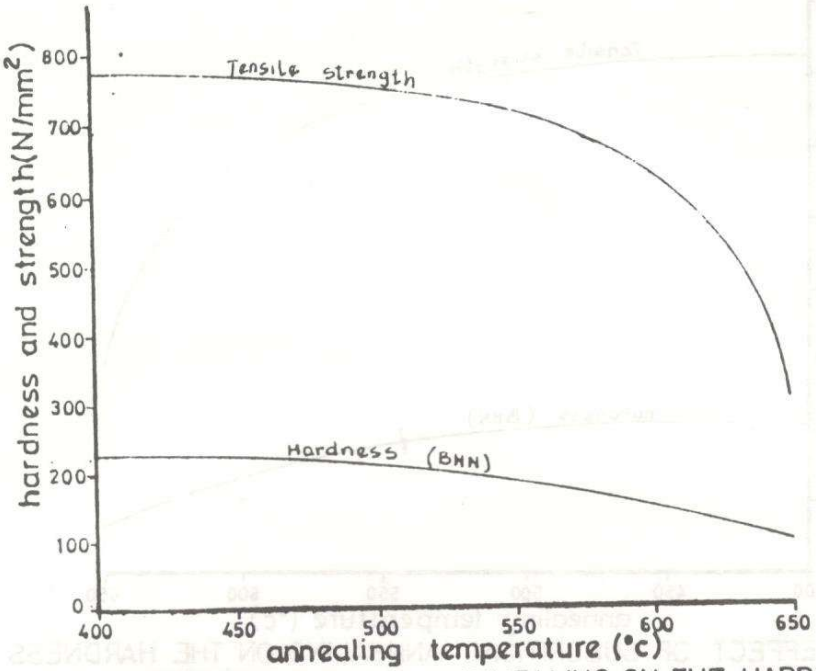



Fig. 9 EFFECT OF SUBCRITICAL ANNEALING ON THE HARDNESS AND STRENGTH OF NST 37-2 STRAIN HARDENED TO 88.89%.

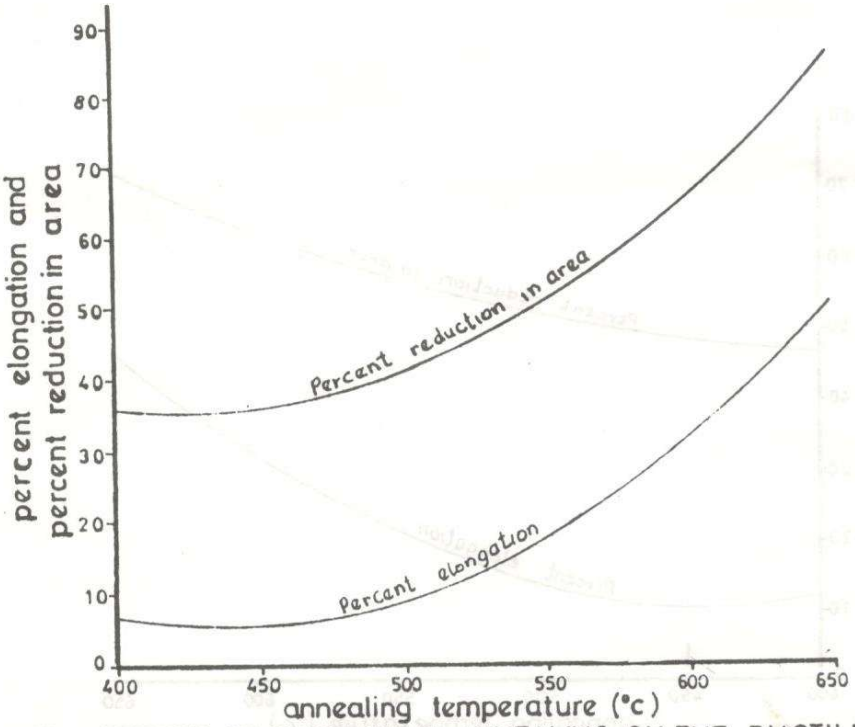



Fig. 10 EFFECT OF SUBCRITICAL ANNEALING ON THE DUCTILITY OF NST 37-2 STRAIN HARDENED TO 88.89%.

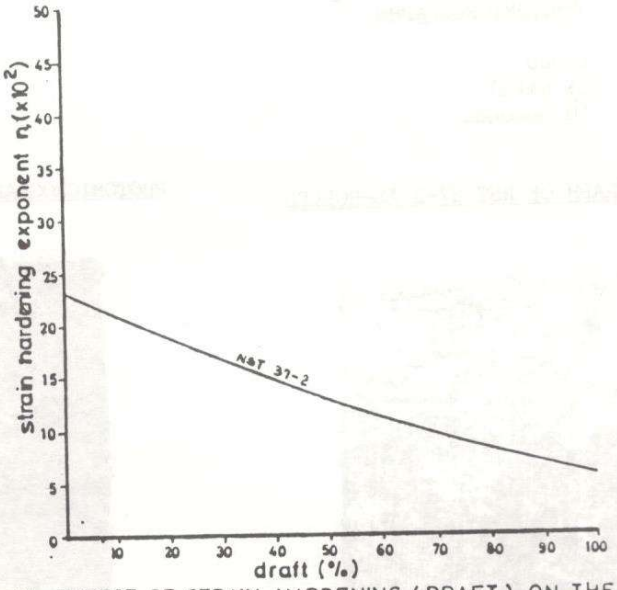



Fig. 11 EFFECT OF STRAIN HARDENING (DRAFT) ON THE STRAIN HARDENING EXPONENT n, OF NST 37-2

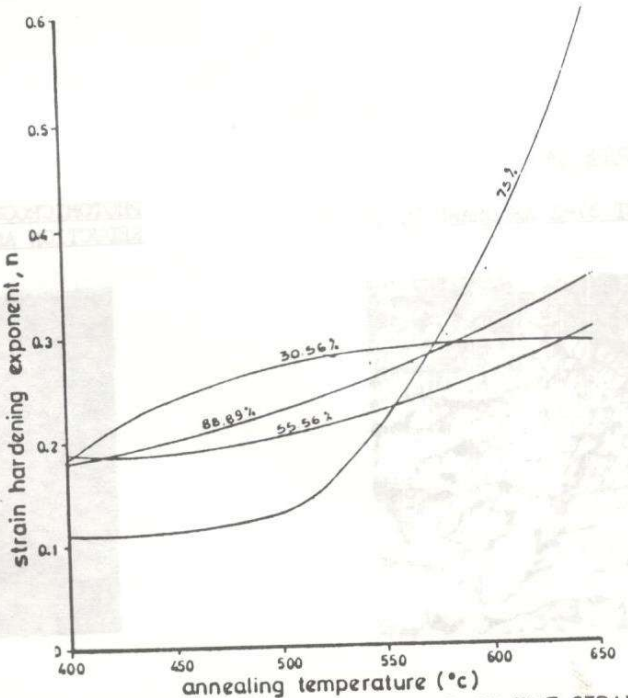



Fig. 12 EFFECT OF SUBCRITICAL ANNEALING ON THE STRAIN HARDENING EXPONENT n OF NST 37-2 STRAIN HARDENED TO 30.36%, 55.56%, 75% AND 88.89%

PHOTOMICROGRAPHS

Magnification : x 500
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Etching time : 10 seconds

FIGURE 13: MICROGRAPH OF NST 37-2 AS-ROLLED

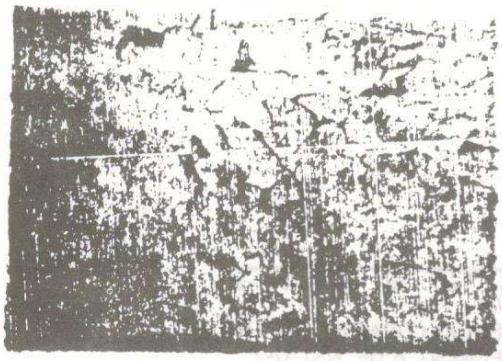


FIGURE 14:

PHOTOMICROGRAPH OF NST 37-2 AS DRAWN TO 30.56%

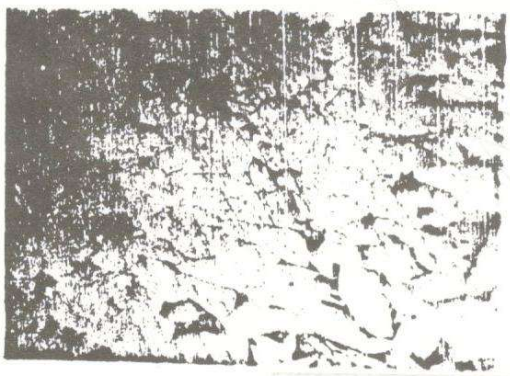


FIGURE 15:

PHOTOMICROGRAPH OF NST 37-2 AS DRAWN TO 55.56%

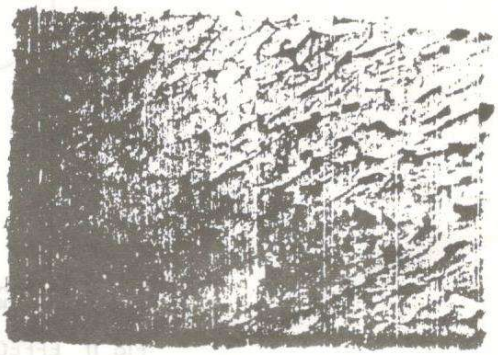


FIGURE 16:

PHOTOMICROGRAPH OF NST 37-2 DRAWN TO 30.56% REDUCTION AND ANNEALED AT 500°C

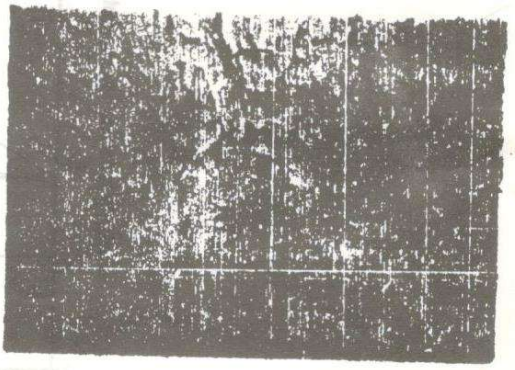


FIGURE 17:

PHOTOMICROGRAPH OF NST 37-2 DRAWN TO 55.56% REDUCTION AND ANNEALED AT 500°C

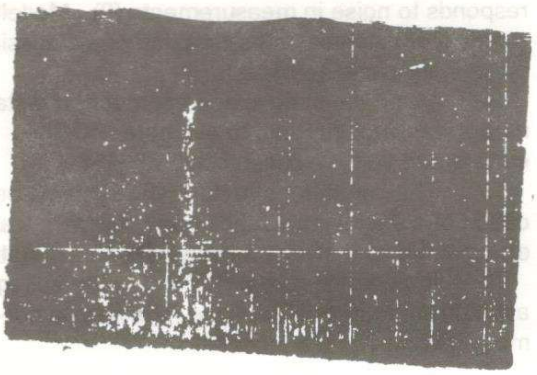


FIGURE 18:

PHOTOMICROGRAPH OF NST 37-2 DRAWN TO 30.56% REDUCTION AND ANNEALED AT 650°C

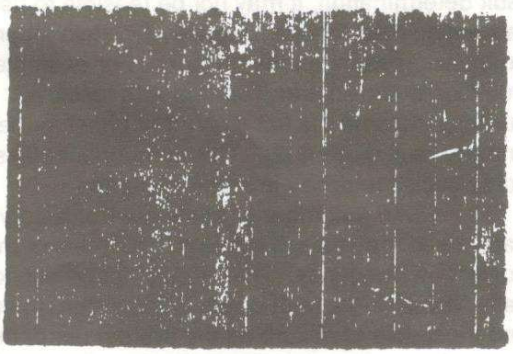


FIGURE 19:

PHOTOMICROGRAPH OF NS 34 LC STRAIN HARDENED TO 55.56% AND ANNEALED TO 650°C

