STRAIN-HARDENING CHARACTERISTICS OF NS 34 LC

ENGR. JOHN ADE AJAYI
Department of Metallurgical & Materials Engineering,
The Federal University of Technology,
P. M. B. 704,
Akure, Ondo State, Nigeria.

ABSTRACT

This paper is based on the research recently carried out on the strain-hardening characteristics of the Nigeria Mild Steel, NS 34 LC, which is used for the manufacturing of nails, barbed wires and office pins among others; the objective is to improve and the drawability of this grade of steel.

The steel is strain-hardened (cold-worked) by wire drawing it at different drafts of 30.56%, 55.56%, 75% and 88.89%. This is followed by sub-critical annealing and metallography. In each case, five mechanical properties - tensile strength, yield stress, hardness, per cent reduction in area and per cent elongation - are observed.

For optimum combination of desired mechanical properties on cold-worked NS 34 LC the steel should not be strain-hardened beyond 75% draft and should be critically annealed at 650°C for soaking time of 15 minutes before further deformation.

INTRODUCTION

It is basically understood that deformation of metals occur principally by the motion of existing dislocations and the creation of many addition dislocations. As the dislocation density increases with cold deformation it becomes more and more difficult for the dislocation to move through the existing forest of dislocation and thus the metal work or strain hardens with increased cold deformation. Although strain-hardening mechanisms are not yet fully understood, the application of the existing knowledge on strain-hardening in engineering is enormous.

Wasatoski[1] observed that the experience of nails manufacturing teaches that excessive wire deformation rate causes trouble during head forming of nails. He found that the ultimate tensile strength (UTS) changes against the deformation of the as-drawn wires. Also, the relationship between yield strength (Y.P) and deformation rate (R) was used.

$$Y.P. = AR^b \rightarrow \text{Log } Y.P. = \text{Log } A + b \log R$$

where Y. P. = Yield strength
R =Reduction rate (%)
A, b = Constants

He was able to use the relationships to determine $\frac{YP}{UTS}$ ratio for all cases before cold deformation and during cold deformation and thus concluded that as $\frac{YP}{UTS} \rightarrow 1$ the brittleness of the material increases while its ductility or drawability decreases. NS 34 LC is a low carbon Nigeria Steel product with average ultimate tensile strength (UTS) of 34kg/mm^2 (340 N/mm^2) which has its billets further processed by hot rolling in the rolling companies.

This becomes the raw materials for the wire drawing mills. At the wire drawing mills, the wire is drawn cold (strain-hardened) to enhance the mechanical strengths of smaller sizes that will be suitable for production of nail, barbed wire, wire netting, electrodes for welding, paper clips, safety pins and binding wires.

It has been observed that during further processing of these wires by nail manufacturing industries that most of the wires had undergone excessive strain-hardening and so they break such that the initial set up for the production has to be re-organized. This invariably causes high product, energy and time wastage. Hence the maximum percentage of cold-work for NS 34 LC prior to sub-critical annealing need to be established as a factor of safety during design for plastic deformation. This is why this close study on the structure-mechanical properties - engineering applications relationships of NS 34 LC during plastic deformation is embarked on and the result should be of tremendous benefits to the users of this grade of steel.

2. EXPERIMENTAL DETAILS

2.1 MATERIALS

6mm - diameter wire rolled products of NS 34 LC weighing 13.5kg were collected from Jos Steel Rolling Mill for wire drawing at Highland Steel and Allied Industries in Jos. The ladle chemical composition and mechanical properties of the material is shown in table 1

2.2 EXPERIMENTAL PROCEDURE

A gage length of 150mm was used[2] for tensile tests and the gage marks along the gage length were 4s (where d is the diameter of the wire under test)[3]. The tensile strength/hardness conversion[4] was used to find their hardness number.

The test pieces of NS 34 LC were strain-hardened by wire-drawing from 6mm diameter as-rolled product to 2mm diameter. That gives a per cent strain-hardening up to 88.89%. To achieve this percentage, the test pieces were drawn to 5mm (30.56% strain-hardening), 4mm (55.5%) strain-hardening), 3mm (75% strain-hardening) and lastly 2mm (88.89% strain-hardening).

The tensile tests were carried out for as-rolled hard-drawn and sub-critically annealed wires using osen Tinus Universal testing machine. The tensile strength, yield strength, elongation, reduction in area and hardness were read from the digital display attached to the machine and the force-extension curve given.

Three temperatures, 400°C, 500°C, 600°C were used to anneal NS 34 LC that were strain-hardened to 30.56%, 55.56%, 75% and 88.89%. The test piece was heated at the furnace rate and the soaked for 15 minutes at the attainment of the required temperature, microstructural investigations on as-rolled, hard-drawn and annealed NS 34 LC were carried out. The test sample was mounted, ground, polished, etched, examined on the microscope and the microstructures snapped by camera to give the photomicrographs.

3. RESULTS AND DISCUSSION

3.1 THE EFFECT OF STRAIN-HARDENING ON THE MECHANICAL PROPERTIES OF NS 34 LC

Table 2 shows the effect of strain-hardening on mechanical properties of NS 34 LC. The curves of mechanical properties versus strain-hardening are shown in figure 1. The tensile test of NS 34 LC as-rolled was found to be 369 N/mm^2 which on strain-hardened to 88.89% was increased to 922 N/mm^2. This is an increase of 150% over a range of 88.89% strain-hardening. The yield strength of as-rolled product was found to be 240 N/mm^2 which was increased to 850 N/mm^2 on strain-hardening to 88.89%

The 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. Percentage reduction in area was reduced on strain-hardening from 42% to 6.25%.

In figure 1, the curves of the ultimate tensile strength and yield strength intercepts at 85% strain-hardening. This is quite significant. Thus NS 34 LC attains full hardness or full brittleness at 85% strain-hardening.

3.2 EFFECT OF SUB-CRITICAL ANNEALING ON THE MECHANICAL PROPERTIES OF NS 34 LC

Table 3 shows the effect of sub-critical annealing on NS 34 LC strain-hardened to 30.56%, 55.56%, 75% and 88.89%.

The curves of mechanical properties versus sub-critical annealing temperatures for NS 34 LC strain-hardened to 30.5%, 55.56%, 75% and 88.89% are shown in figures 2, 3, 4 and 5. The tensile strength and hardness were found to reduce as the annealing temperature increases. The per centage elongation and reduction in area were found to reduce as the annealing temperature increases.

3.3 EFFECTIVE OF STRAIN-HARDENING ON STRAIN-HARDENING EXPONENT AND ANNEALING TEMPERATURE

Table 4 shows the effect of strain-hardening on strain-hardening exponent, n. When the mathemati-

cal relationship between true stress and true strain in the plastic region as expressed by Holloman equation[5] $\sigma = k\varepsilon^n \rightarrow \log \sigma = \log k + n \log \varepsilon^n$ was applied, the strain -hardening exponent for each strain-hardened material was determined. From figure 6, it is seen that strain-hardening component, n, decreases as strain-hardening decreases. But n is an index of drawability.

The reduction in drawability of NS 34 LC became much more pronounced as from 75% strain-hardening which is equivalent to 3mm diameter hard-drawn wire.

Table 5 shows the effect of sub-critical annealing on the strain-hardening component, n, of strain-hardened NS 34 LC.

As a result of applying the sub-critical annealing heat treatment to the strain-hardened NS 34 LC, the effect of the strain-hardening is seen disappearing as from 400°C up to 650°C at which the material is fully restored to its previous condition before strain-hardening. This is obvious from figure 7.

3.4 EFFECT OF STRAIN-HARDENING ON THE MICROSTRUCTURE OF NS 34 LC

A close examination of the microstructure of the as-rolled sample reveals that pearlite phases exist in ferrite matrix in a fairly regularly arranged elongated manner. But when cold-worked to 30% draft, the pearlite aggregates become finer and when strained-hardened to 55.56%, the pearlite aggregate becomes very fine. It can be seen that as the strain-hardening increases, more pearlite phases are forced into the ferrite structure.

The hardness values (in BHN) for as-rolled sample (0% strain-hardening), 30% strain-hardening and 55.56% strain-hardening are 105.43, 178.14 and 216.79% respectively.

Thus it is assetible that strain-hardening engenders fines of grain sizes of pearlite phase of a sample and this in turn enhances the sample's hardness.

3.5 EFFECT OF SUB-CRITICAL ANNEALING ON THE MICROSTRUCTURE OF STRAIN-HARDENED NS 34 LC

Figures 12, 13, 14 and 15 are photomicrographs of NS 34 LC strain-hardened to 30.56% and annealed to 500°C (figure 12) and 650°C (Figure 14) and NS 34 LC strain-hardened to 55.56% and annealed to 500°C (figure 12) and 650°C (figure 15). The ferritic nature of the microstructure increases as the annealing temperature increases. This implies that the effect of strain-hardening on the microstructure was annulled by process annealing.

The higher the sub-critical annealing temperature, the greater is the neutralising effect of process annealing on the strain-hardening of a sample. This is explainable from the annealing-recrystallization-grain growth cycle.

4. CONCLUSION

On the basis of the result of this investigation on the strain-hardening characteristics of NS 34 LC (for drawability improvement) the following conclusions can be made:

(1) The microstructures of the original NS 34 LC as-rolled products are distorted during strain-hardening.

(2) The ratio $\frac{\text{Yield strength}}{\text{Ultimate tensile strength}} \rightarrow 1$ at 85% strain-hardening (figure 8). Thus NS 34 LC attains its full hardness or full brittleness at 85% strain-hardening and as factor of safety against fracture, should not be strain-hardened beyond 75% reduction annealing.

(3) 650°C annealing temperature and a soaking time of 15 minutes should be used to remove the effect of previous strain-hardening cold-working on NS 34 LC.

(4) The charts so provided should be used as a guide in processing this grade of Nigeria steel. If there be need for a process anneal cycle, sub-critical annealing on various per cent strain-hardened material, the annealing temperature required can be determined having known the per cent strain-hardening of the material.
The publications of Standard Organization of Nigeria are recommended to be used in conjuction with these charts.

ACKNOWLEDGEMENT

The author is grateful to National Metallurgical Development Centre, Steel Rolling Company, and Highland Steel & Allied Industries all in Jos, Nigeria for making available the research facilities and materials used for this work.

REFERENCES

1. **Wusatowski, A (1984):** Recommendation for the Selection of Wire for Nail Manufacturing, National Steel Council, Metal Working Section, Jos, Nigeria, pp 6-7

2. **Nigerian Standard Organisation (NSO), (1973):** Methods for Torsion and Tensile Testing of Steel Wires, Federal Ministry of Industries, Lagos, Nigeria.

3. **American Society for Testing and Materials (ASTM), (1996):** Metals-Mechanical Testing elevated and Low Temperature Tests, Metallography Vol. 03.01, Section 3, P. 644

4. **Kalpakjiam, S (1989);** Manufacturing Engineering Technology Addison Wesley Publishing Company, U. S. A. P. 78.

5. **The Institute of Materials:** Material Science and Technology (MST) (1992): Vol. 8 No. 12 Kerthwakelam, London, PP 188 1075.

Table 1: NS 34 LC DESIGNATION, COMPOSITION AND MECHANICAL PROPERTIES

NST - **Nigeria Steel**
34 - **Ultimate tensile strength (UTS) = 34 kg/mm² (340 N/mm²)**
LC - **Low Carbon**

Ladle chemical Compostion (W %)	
Carbon = 0.06-0.12	Ultimate tensile strength =305-440(N/mm²)
Silicon (sil) = 0.18-0.28	Yield strength = 220 N/mm2 (minimum)
Manganese (Mn) = 0.04-0.60	Percentage elongation = 40% (minimum).

Table 2: Effect of Strain Hardening on the Mechanical Properties of NS 34 LC

S/No.	Steel Code	Diameter mm	Present Strain hardening	Tensile Stress (N/mm2)	Yield Stress (N/mm2)	Percent reduction in area %	Hardness (BHN)
1		6.0	0.00	369.0	240.0	42.00	105.43
2	MS 34	5.0	30.56	623.5	570.0	10.00	178.14
3		4.0	55.56	758.7	610.0	9.40	216.77
4.	LC	3.0	75.00	865.6	760.0	8.30	247.31
5		2.0	88.89	922.0	850.0	6.25	263.42

Table 3 Effect of Subcritical Annealing on Strain Hardened NS 34-LC

S/No	Annealing Temperature (°C)	Tensile stress (N/mm2)	Percent elongation (%)	Percent reduct-area (%)	Hardness (BHN)
	30.56% strain-hardened				
1	400	559.0	17.5	64.0	159.7
2	500	548.8	20.0	64.0	156.8
3	650	364.6	50.0	75.0	104.2
	55.56% strain-hardened				
1	400	585.6	12.8	51.0	167.3
2	500	570.1	21.9	57.8	162.9
3	650	305.5	43.8	72.4	87.3
	75.00 % strain-hardened				
1	400	591.9	12.5	46.2	169.1
2	500	589.2	16.7	51.0	168.35
3	650	271.6	45.8	71.6	77.6
	88.89 % strain-hardened				
1	400	619.1	6.9	43.8	176.9
2	500	605.2	12.5	51.0	172.95
3	650	305.7	50.0	34.0	87.3

TABLE 4 EFFECT OF STRAIN HARDENING ON THE STRAIN HARDENING EXPONENT OF NS 34 LC

S/No	Percent Strain hardening	Strain hardening exponent, n
1	0	0.36
2	30.56	0.30
3	55.56	0.23
4	75.00	0.09
5	88.89	0.04

TABLE 5 EFFECT OF SUBCRITICAL ANNEALING ON THE STRAIN HARDENING EXPONENT, 'n' OF STRAIN HARDENED NS 34 LC

Percent strain hardening	Strain Hardening Exponent		
	Annealed at 400°C	Annealed at 500°C	Annealed at 650°C
30.56	0.173	0.250	0.330
55.56	0.129	0.171	0.357
75.00	0.117	0.148	0.436
88.89	0.278	0.385	0.596

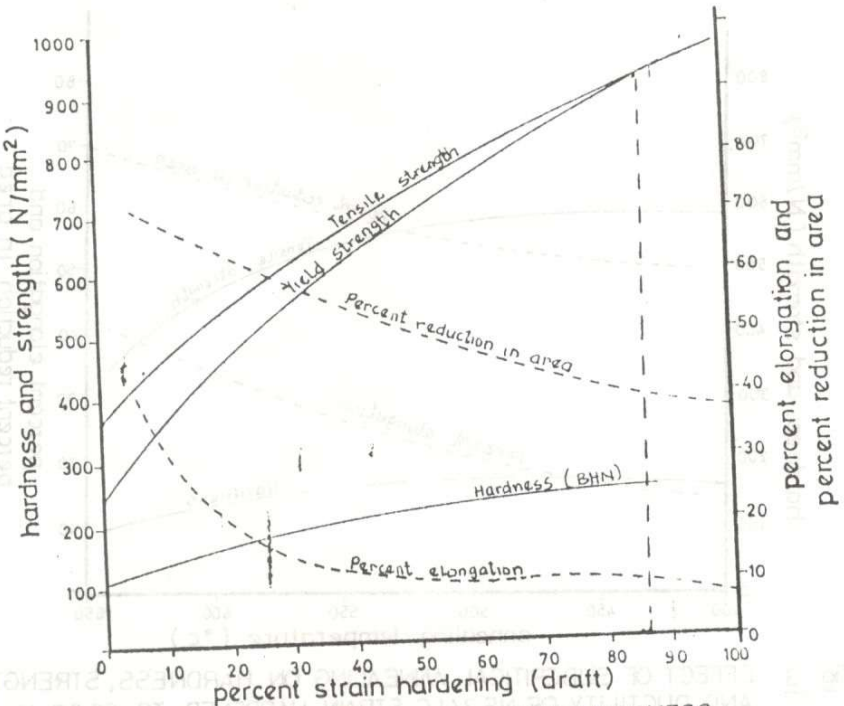


Fig. 1. EFFECT OF STRAIN HARDENING ON THE HARDNESS, STRENGTH AND DUCTILITY OF NS 34 LC.

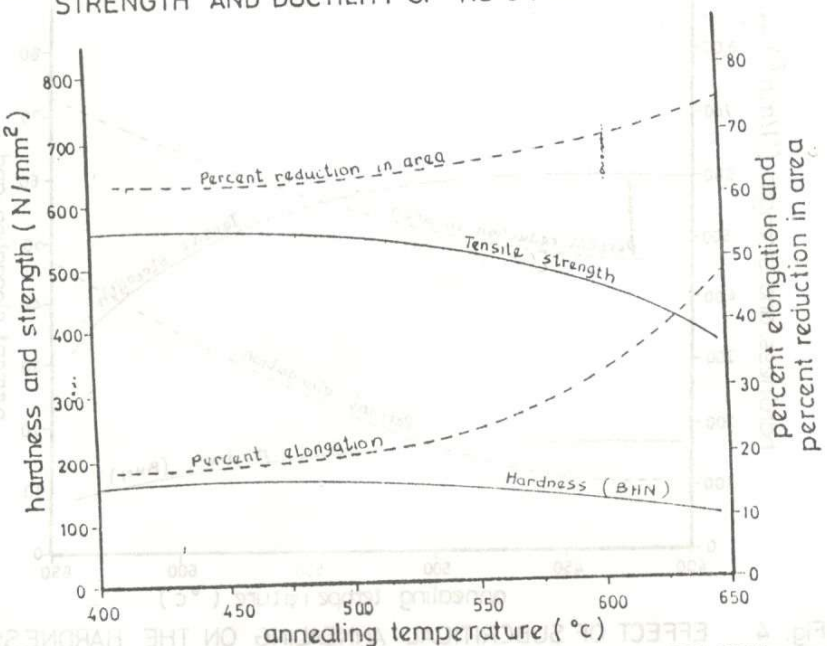


Fig 2 EFFECT OF SUBCRITICAL ANNEALING ON HARDNESS, STRENGTH AND DUCTILITY OF NS34LC STRAIN HARDENED TO 30.56 %

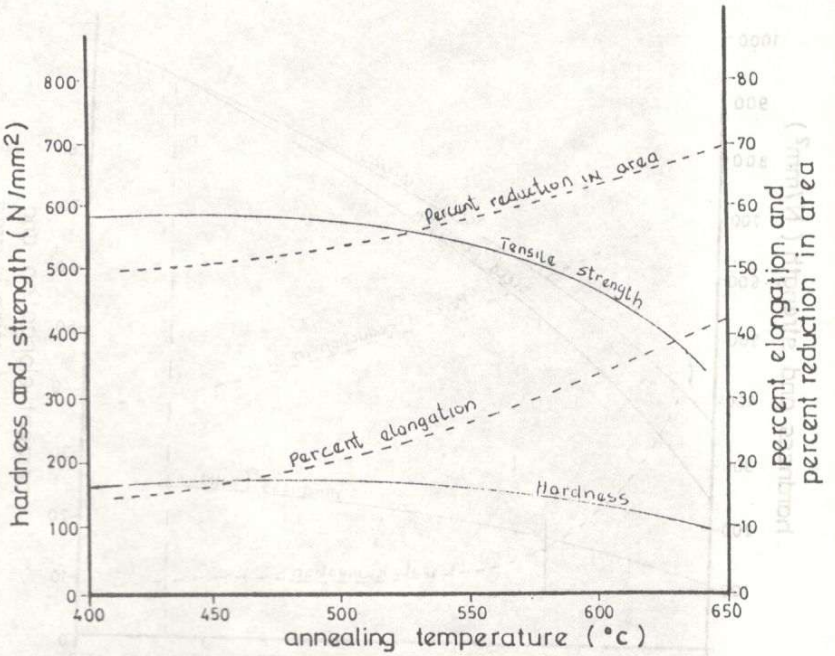


Fig. 3 EFFECT OF SUBCRITICAL ANNEALING ON HARDNESS, STRENGTH AND DUCTILITY OF NS 34LC STRAIN HARDENED TO 55.56 %

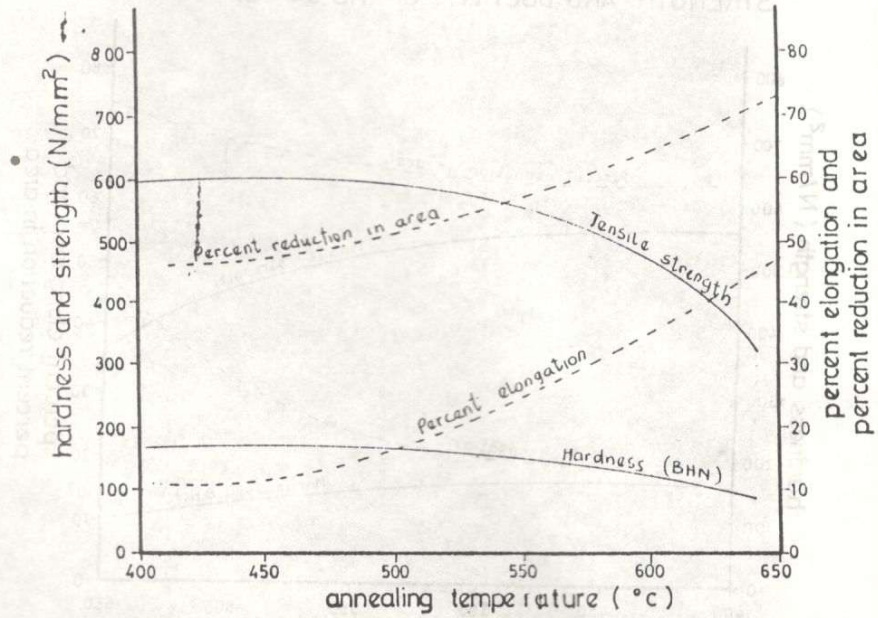


Fig. 4 EFFECT OF SUBCRITICAL ANNEALING ON THE HARDNESS STRENGTH AND DUCTILITY OF NS 34LC STRAIN HARDENED TO 75 %

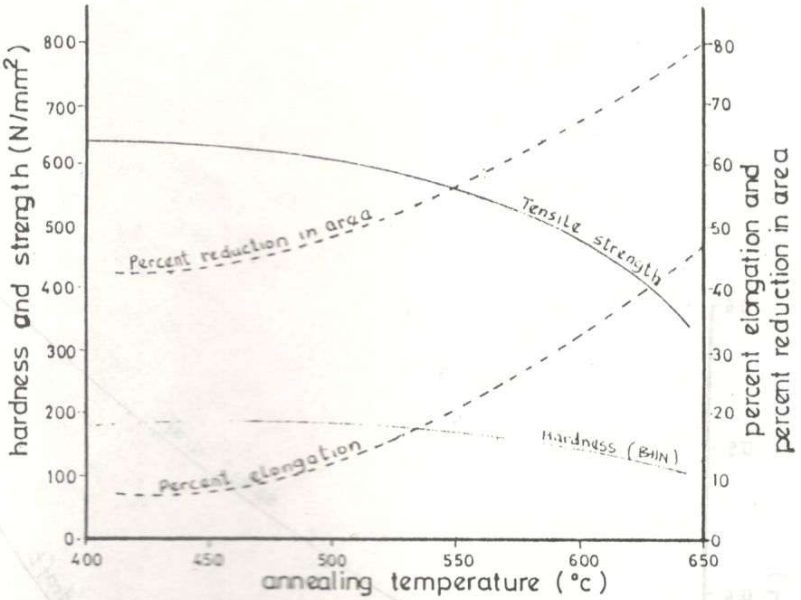


Fig. 5. EFFECT OF SUBCRITICAL ANNEALING ON THE HARDNESS, STRENGTH AND THE DUCTILITY OF NS34LC STRAIN HARDENED, TO 88.89 %

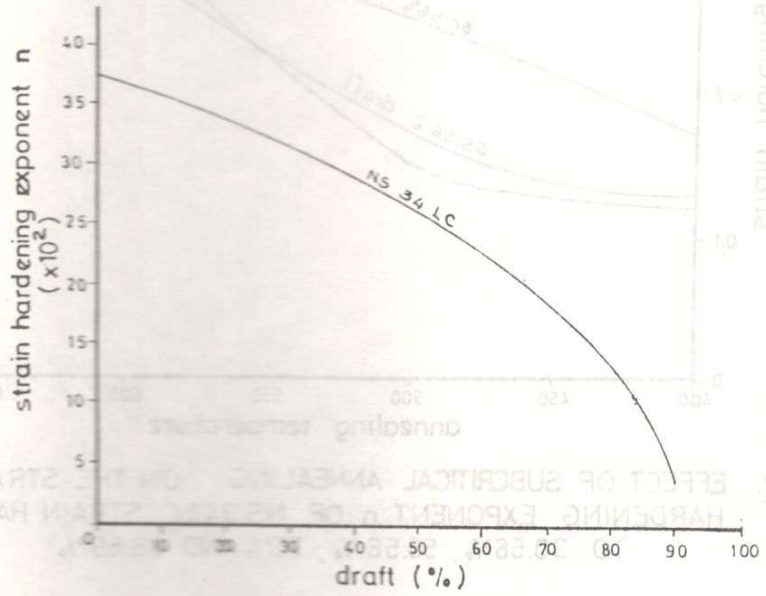


Fig. 6. EFFECT OF STRAIN HARDENING (DRAFT) ON STRAIN HARDENING EXPONENTS, n, (OR DRAWABILITY) OF NS 34 LC

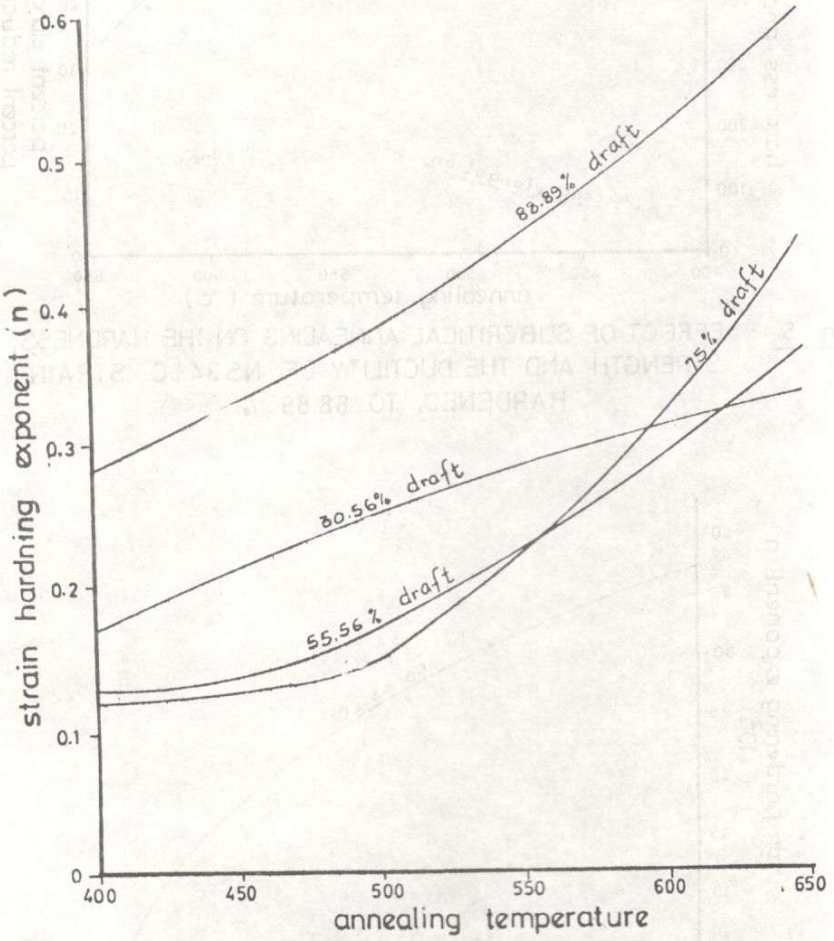


Fig. 7. EFFECT OF SUBCRITICAL ANNEALING ON THE STRAIN HARDENING EXPONENT n OF NS 34 LC STRAIN HARDENED TO 30.56%, 55.56%, 75% AND 88.89%

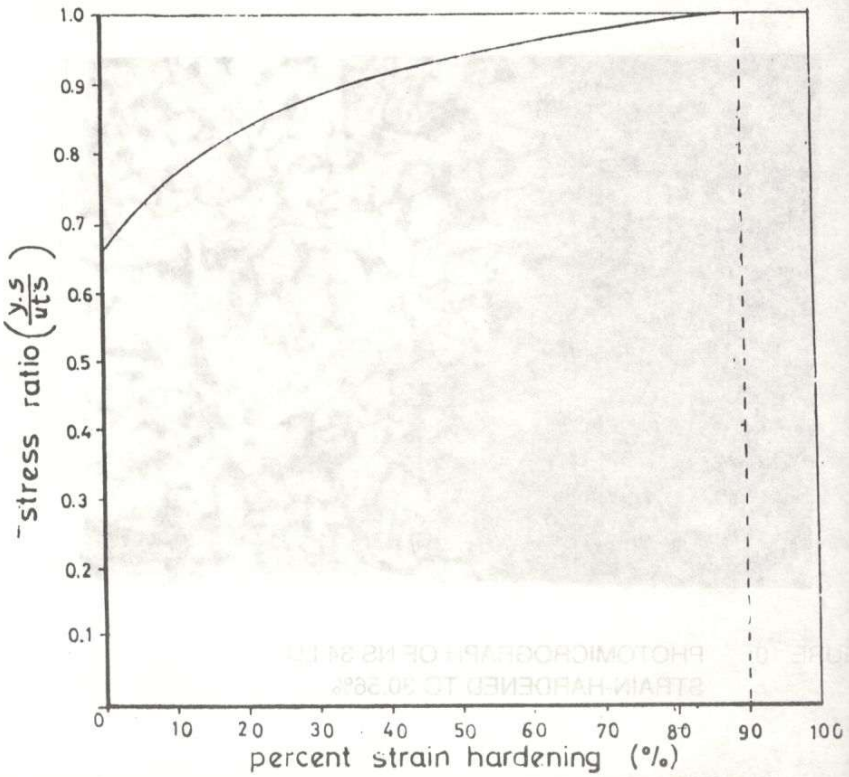


Fig 8 EFFECT OF STRAIN HARDENING ON THE STRESS RATIO (ys/uts) OF NS 34 LC

PHOTOMICROGRAPHS

Magnification : x 500

Etchant : 2% nital

Etching time : 10 seconds

FIGURE 9: MICROGRAPH OF NS 34 LC AS-ROLLED



FIGURE 10: PHOTOMICROGRAPH OF NS 34 LC STRAIN-HARDENED TO 30.56%



FIGURE 11: PHOTOMICROGRAPH OF NS 34 LC AS DRAWN TO 55.56%



FIGURE 12: PHOTOMICROGRAPH OF NS 34 LC DRAWN TO 30.56% AND ANNEALED AT 500 C

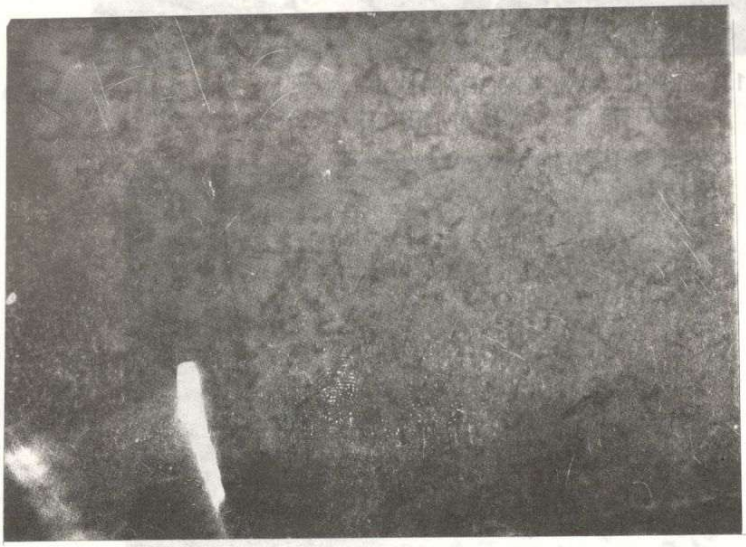


FIGURE 13: PHOTOMICROGRAPH OF NS 34 LC STRAIN-HARDENED TO 55.56% AND ANNEALED TO 500 °C



FIGURE 14: PHOTOMICROGRAPH OF NS 34 LC STRAIN-HARDENED TO 30.56% AND ANNEALED TO 650°C



FIGURE 15: PHOTOMICROGRAPH OF NS 34 LC STRAIN-HARDENED TO 55.56% AND ANNEALED TO 650°C

