PB-223 686

# THE FORMABILITY OF PRECIPITATION HARDENED STEELS

N. A. Cantalejos, et al

BISRA-The Corporate Laboratories of British Steel Corporation
London, England

August 1973

PB 223 686

CORPORATE DEVELOPMENT LABORATORY

MT/4/73

British Steel Corporation

# The Formability of Precipitation Hardened Steels

N.A. Cantalejos and R.A. Maynard



OPEN

CONTENTS



Metallurgy Department
Corporate Development Laboratory
British Steel Corporation
Hoyle Street
Sheffield S3 7EY

# THE FORMABILITY OF PRECIPITATION HARDENED STEELS

N. A. Cantalejos and R. A. Maynard

(To be presented at the "Third International Conference on the Strength of Metals and Alloys", Cambridge, UK., 20 - 25 August 1973.)

## INTRODUCTION

The main concern of this research programme is the study of the cold formability of high strength sheet steels having yield strengths of the order of 350 N/mm². The interest in forming these steels originates with the increasing usage of strong steels in thin sections in a wide range of pressing applications where the formed component is required to withstand severe service conditions: Dewsnap et al [1] have detailed many of these uses for hot band. Typically, strengths of up to 500 N/mm² are being demanded, in contrast to the 160 - 240 N/mm² found in the majority of steels currently sold for cold forming[1]. The problem is that, generally, the higher the strength of the material, the more difficult it is to form.

In sheet forming, failure usually results from plastic instability, the occurrence of which is controlled by the work-hardening capacity of the metal. That raising the strength of a metal invariably reduces its capacity for sustained work-hardening was amply demonstrated by Gensamer[2], who observed that, in a wide range of ferritic steels, the exponent n in the Ludwik representation of the stress-strain relation - $\bar{\sigma} = K\bar{\epsilon}^n$ - decreases as the flow stress at a constant strain increases.

The occurrence and form of a failure are strongly dependent upon the stresses and strains imposed upon the workpiece[3,4]. Thus in any forming operation (e.g. roll-forming) which imposes largely compressive states of stress, limitation of forming by plastic instability is impossible. Further, the initiation and propagation of fracture processes are suppressed by compressive mean stresses. The result is that such operations are comparatively tolerant of the use of high strength steels. In the stretching of thin sheets, two varieties of instability are recognised, due to Swift [5] and Hill[6]. For stress ratios $\sigma_2/\sigma_1 = 0.5$ (where $\sigma_1$ and $\sigma_2$ are respectively the maximum and intermediate principal stresses) it is possible that localisation of flow according to Hill's theory [6] can be achieved, resulting in rapid failure, but only the diffuse instability resulting from Swift's maximum load criterion can occur in sheets deformed so that all directions in the plane of the sheeet are extended. Diffuse instabilities are manifested as extensive and slowly localising strain concentrations, so that it is possible that useful post-instability straining might be obtained. In order to gain maximum benefit from this phenomenon, it is obviously necessary to defer the onset of ductile fracture, which means reducing the incidence of the second phase particles likely to yield void nucleation.

A particular model precipitation system, Fe-Cu, was chosen for this investigation, which is aimed at determining the conditions under which ductile fracture limits cold formability. In these alloys, hardening is produced by the precipitation of soft particles of $\epsilon$- Cu[7,8]: the strengthening mechanism has been discussed in detail by Russell and Brown[9].

## EXPERIMENTAL METHODS

Two alloys, whose compositions are shown in Table 1, were prepared as 23 Kg vacuum melts. The presence of nickel is necessary in these materials to ensure adequate hot workability[10].

TABLE 1 THE COMPOSITIONS OF THE ALLOYS USED

| Alloy | C, wt% | Ni, wt% | Cu, wt% |
|---|---|---|---|
| R | 0.009 | 0.68 | 0.72 |
| S | 0.007 | 0.50 | 0.97 |

These alloys were converted into 0.7 mm thick strip by suitable forging, hot rolling and final 80% cold rolling treatments. All materials were annealed and solution-treated for 1 hour at 800°C, followed by water quenching. Ageing curves for the two alloys were obtained in the usual way, and suitable material conditions for mechanical testing selected as described below.

Normal tensile testing procedures were used to derive strength and ductility measurements, in addition to work-hardening exponents, n, and plastic anisotropy parameters, $\bar{r}$. ($\bar{r}$ is the average for all directions of tensile testing in the sheet plane of the ratio of width strain: thickness strain, determined as $\bar{r} = \frac{1}{4}(r_{90} + 2r_{45} + r_0)$.

Hydraulic bulge tests were performed on sheets on which a reference grid of 5 mm diameter circles had been electrochemically etched, surface strains being obtained from the final dimensions of these circles. Both circular and elliptical dies were used, the latter having a major axis : minor axis ratio of 1.427.

## RESULTS

It was found that ageing at 550°C in both alloys yielded the most convenient combination of strength and reasonable ageing times. Figure 1 shows the ageing curves obtained at this temperature, together with the treatments selected for mechanical test specimens.

Yield stresses varied with ageing time in much the same way as did hardnesses: values in the solution treated and peak hardness conditions were respectively 176 $N/mm^2$ and 261 $N/mm^2$ (R), and 196 $N/mm^2$ and 351 $N/mm^2$ (S). Uniform elongations in the tensile test did not show a pronounced minimum value at peak hardness, falling from 25% to 9% (R) and 20% to 8% (S) during the ageing times used.

The values of $\bar{r}$ and n obtained are more important from the sheet testing viewpoint, and are plotted in detail in figures 2 and 3, where it will be seen that material "R" exhibits pronounced minima in both $\bar{r}$ and n in the peak hardness condition.

The heights, h, of bulge tested specimens at fracture were estimated, and surface and thickness strains measured with a micrometer, precision dividers or a binocular microscope with measuring eyepiece, as appropriate. Values of the ratio bulge height:bulge radius (h/r) are given in Table 2, together with corresponding values inferred (using experimental $\bar{r}$ and n values) from Wang and Shammamy's theoretical treatment of hydraulic bulging[11] based on Hill's incremental plasticity theory[12]. The same source yielded the theoretical polar thickness strains at instability found in Table 2.

The Keeler[13] - Goodwin[14] forming limit diagram (FLD) is a widely used technique for the graphical representation of certain forming properties. It is simply a plot of the major ($\epsilon_1$) and minor ($\epsilon_2$) surface strains at failure under various sheet testing conditions. "Failure" in a sheet forming context may be either fracture or instability in cases where unsightly marks on the finished pressing must be avoided. FLD's have a common general shape (see Figure 4) where the shaded band indicates the range of strains over which failure is found. In spite of certain limitations[3], the FLD is the most convenient way of demonstrating the results of this work.

Two limiting strain combinations ($\epsilon_1$ and $\epsilon_2$) were derived in this investigation from bulged samples ($\epsilon_1$ and $\epsilon_2$ both positive). One combination is the value corresponding to fracture; the other, obtained by extrapolation of the smooth portions of the graphs of $\epsilon_1$ and $\epsilon_2$ against position in the bulge, was assumed to correspond reasonably well with the strain state at instability. In plane strain ($\epsilon_2 = 0$), $\epsilon_1$ was taken to be equal to n, which arises theoretically from both the Hill and Swift instability criteria (see 15). The theoretical limiting combination in uniaxial tension is included for completeness: in this case $\epsilon_1 = 2n$ and $\epsilon_2 = -2n\left(\frac{r}{1+r}\right)$. The FLD's for material R (in conditions $R_0, R_1, R_2$) and S (conditions $S_0, S_1, S_2$) are plotted in Figures 5 and 6 respectively.

It will be clear that in general, the values of $\epsilon_1$ and $\epsilon_2$ in bulged specimens (and thus the level of the limiting strain band) are strongly dependent upon n. The exception to this behaviour is the over-aged "R" material ($R_2$) whose limiting strains are anomalously low in certain samples. As would be expected, the forming limits of the two solution-treated materials are virtually identical: small solid solution additions thus produced little change in the strain development pattern.

Examination of the fracture surfaces of both materials showed that void coalescence was substantially responsible for failure (Figure 7). Large numbers of small inclusions were found associated with the superficial dimples: metallographic examination of sections taken near a fracture demonstrated that inclusions were associated with the majority of the large number of small voids present.

## DISCUSSION

The range of values of $\bar{r}$ and n encountered in this work is comparatively limited, making evaluation of the effects of these parameters on stretch-forming very difficult: however, Table 2 shows a limited tendency for a higher n value to be associated with a greater h/r ratio, in agreement with theoretical predictions[11].

**TABLE 2 THEORETICAL AND EXPERIMENTAL BULGE TEST PARAMETERS**

| | $\bar{r}$ | n | Polar thickness strain (theory) $\epsilon_t$ | Polar thickness strain (expt) $\epsilon_t$ | h/r (theory) | h/r (expt) |
|---|---|---|---|---|---|---|
| $R_0$ | 1.2 | 0.25 | 0.66 | 0.55 | 0.63 | 0.72 |
| $R_1$ | 1.2 | 0.22 | 0.64 | 0.47 | 0.61 | 0.62 |
| $R_2$ | 1.4 | 0.25 | 0.66 | 0.51 | 0.62 | 0.64 |
| $S_0$ | 1.2 | 0.24 | 0.65 | 0.50 | 0.62 | 0.68 |
| $S_1$ | 1.5 | 0.20 | 0.63 | 0.47 | 0.59 | 0.60 |
| $S_2$ | 1.4 | 0.19 | 0.62 | 0.45 | 0.59 | 0.60 |
| $S_3$ | 1.5 | 0.18 | 0.62 | 0.44 | 0.58 | 0.60 |

| BIBLIOGRAPHIC DATA SHEET | 1. Report No. | 2. | 3. Recipient's Accession No. PB-233 658 |
|---|---|---|---|
| 4. Title and Subtitle<br>The formability of Precipitattion hardened steels. | | | 5. Report Date<br>August 1973 |
| | | | 6. |
| 7. Author(s)<br>N. A. Cantalejos and R. A. Maynard | | | 8. Performing Organization Rept. No. MT/4/73 |
| 9. Performing Organization Name and Address<br>BISRA - THE CORPORATE LABORATORIES OF THE BRITISH STEEL CORPORATION, HOYLE STREET, SHEFFIELD S3 7EY. | | | 10. Project/Task/Work Unit No. |
| | | | 11. Contract/Grant No. |
| 12. Sponsoring Organization Name and Address | | | 13. Type of Report & Period Covered |
| | | | 14. |
| 15. Supplementary Notes<br>NTIS authorised to reproduce and sell. | | | |

16. Abstracts


The main concern of this research programme is the study of the cold formability of high strength sheet steels having yield strengths of the order of 350 N/mm$^2$. The interest in forming these steels originates with the increasing usage of strong steels in thin sections in a wide range of pressing applications where the formed component is required to withstand severe service conditions. Typically, strengths of up to 500 N/mm$^2$ are being demanded, in contrast to the 160-240 N/mm$^2$ found in the majority of steels currently sold for cold forming. The problem is that, generally, the higher the strength of the materials, the more difficult it is to form.


17. Key Words and Document Analysis. 17a. Descriptors

Pressing (forming)
Formability
Precipitation hardening steels
Metal sheets

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

| 18. Availability Statement | 19. Security Class (This Report) UNCLASSIFIED | 21. No. of Pages 47 |
|---|---|---|
| | 20. Security Class (This Page) UNCLASSIFIED | 22. Price $3.00-1.45 |

FORM NTIS-35 (REV. 3-72)



USCOMM-DC 14952-P72

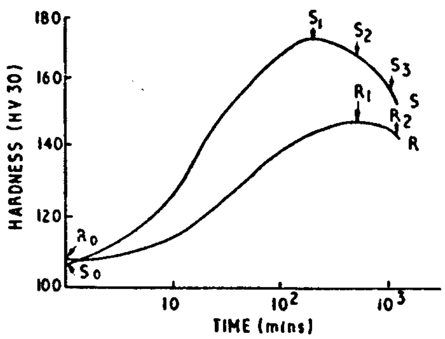


FIG. 1 THE VARIATION OF HARDNESS WITH AGEING TIME AT 550°C FOR Fe-0·68 Ni-0·72 Cu (R) AND Fe-0·50 Ni-0·97 Cu (S)

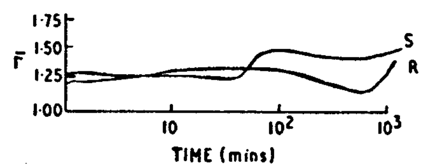


FIG.2 THE VARIATION OF $\bar{r}$ $(=\frac{1}{4}(r_0+2r_{45}+r_{90}))$ WITH AGEING TIME AT 550°C

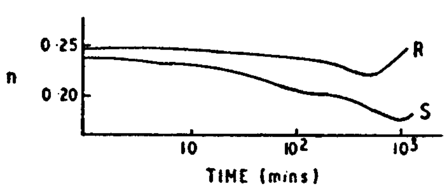


FIG.3 THE VARIATION OF n WITH TIME OF AGEING AT 550°C

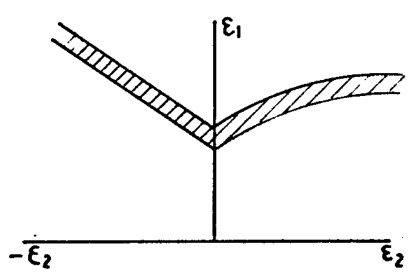


FIG.4 SCHEMATIC FLD AFTER KEELER (13) AND GOODWIN (14)

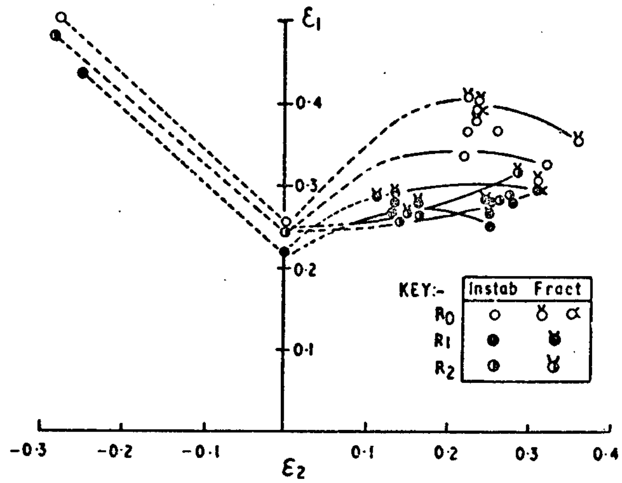


FIG.5 THE FLD's OF MATERIAL R AFTER VARIOUS AGEING TREATMENTS

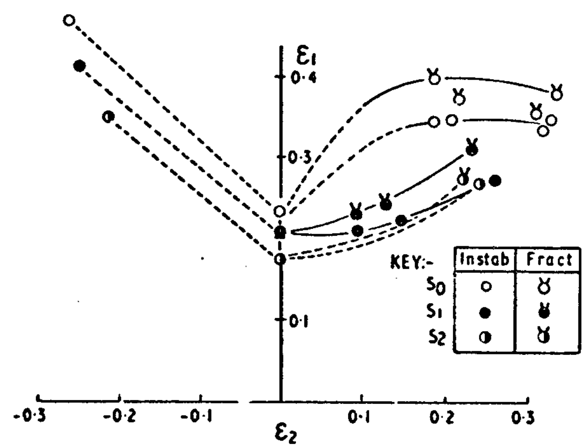


FIG.6 THE FLD's OF MATERIAL S AFTER VARIOUS AGEING TREATMENTS

The value of a high n value, practically, is that high work hardening assists in the prevention of strain concentrations by spreading strain from highly work-hardened regions to lightly work-hardened regions. The general conclusion that most strengthening mechanisms tend to decrease n, thereby restricting cold formability, is therefore supported by this work.

The absolute values of h/r at instability compare remarkably well with Wang and Shammamy's calculated values. Voids initiated by inclusions would seem to be exerting an insignificant effect on the general development of a bulge, although the development of failure after instability clearly arose from void coalescence. On the other hand, this agreement may be fortuitous, since the polar thickness strains at instability and severely overestimated by calculation: this reinforces a previous application of the theory[11] to results of Bramley and Mellor[16].

Summarising, the hardening of iron by dispersions of copper particles restricts the accommodation of strain prior to failure in stretched sheets. The principal cause of this effect is the commensurate reduction of work-hardening capacity with increase in strength level. Fracture is controlled by the coalescence of voids nucleated on non-metallic inclusion particles, pointing to the need for material cleanness if useful post-instability strain is to be obtained.

REFERENCES

1. Dewsnap, R. F., Keane D. M. and Branson, J. R., "Effect of second phase particles on mechanical properties", ISI Conference Volume, p. 190, (1971).
2. Gensamer, M., Trans ASM 36, 30 (1946).
3. Wilson, D. V., in ref. 1., p. 28.
4. Dillamore, I. L., Hutchinson, W. B. and Morris, P. L., in ref. 1., p. 190.
5. Swift, H. W., J. Mech. Phys. Solids 1, 1 (1952).
6. Hill, R., J. Mech. Phys. Solids 1, 19 (1952).
7. Hornbogen, E., Trans ASM 57, 120 (1964).
8. Fujii, A., Nemoto, M., Suto, H, Monma, K. Trans. Jap. IM 9 (Suppl), 374 (1968).
9. Russell K. C. and Brown, L. M., Acta Metall. 20, 969 (1972).
10. Gregg J. L., and Daniloff, B. N., "The alloys of copper and iron", McGraw-Hill, N. Y., (1934).
11. Wang, N. M. and Shammamy, M. R., J. Mech. Phys. Solids 17, 43 (1969).
12. Hill, R., "The mathematical theory of plasticity", OUP (1950).
13. Keeler, S. P., Sheet Met. Ind. 42, 683 (1965).
14. Goodwin, G. M., Proc. 5th Biennial Cong., Int. Deep Drawing Res. Group, Torino, (Italy) (1968).
15. Pearce, R., Proc. 7th Biennial Conf., Int. Deep Drawing Res. Group (1972).
16. Bramley A. N. and Mellor, P. B., Int. J. Mach. Tool Des. Res. 5, 43 (1965).

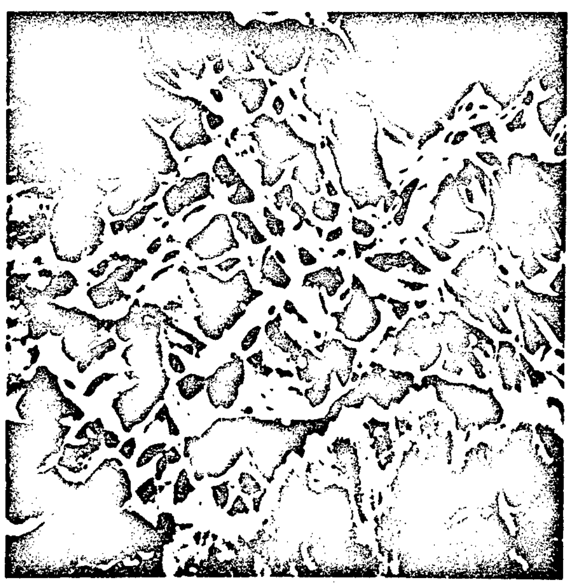

FIG. 7 TYPICAL FRACTURE APPEARANCE OF A FAILED BULGE IN MATERIAL $R_2$ (x 790)

JD. 30.4.73.

END
DATE
FILMED
11-6-73
NTIS