JOURNAL OF MATERIALS SCIENCE 10 (1975) 641–646

Effect of cold work and heat-treatment on the mechanical properties of a wire drawn metastable stainless steel

JOHN NUNES, ALBERT MARTIN
Brunswick Corporation, Materials Research Technical Products Division, Skokie, Illinois, USA

Tensile strengths in excess of 600 × 10^3 psi* were obtained in a Type 18-8 stainless steel using relatively simple thermomechanical treatments involving cold working after solution annealing and intermittent heat-treatments. The strength developed strongly depended on the hardness and amount of martensite formed as well as the maintenance of high work-hardening rates at large deformation strains. For a given level of cold work, martensite is shown to transform more rapidly using material annealed in the carbide precipitation temperature range as this tends to increase the M_d temperature. The volume fraction martensite formed by wire drawing is shown to be related to the square of the deformation strain. Also shown are the effects of annealing temperature and cold work on the elastic modulus.

1. Introduction

The most effective way to strengthen metastable austenitic stainless steel is by cold working them below their M_d (strain induced) martensitic transformation temperature [1-5]. Strength increases obtained in this manner are directly related to the amount of martensite formed and to work hardening of the austenite and martensite [1, 2]. In these alloys, the M_d temperature and martensite hardness are strongly influenced by the carbon and nitrogen content in solution [1, 3, 6, 7]. Slight increases of either carbon or nitrogen have been found to strongly raise the martensitic hardness and at the same time increase the austenite stability by lowering the M_d temperature. It is also known that the austenite stability can be decreased by precipitating these as well as other stabilizing elements from solution [8]. This process is commonly called austenite "conditioning" and is used to raise the athermal martensite transformation temperature, M_s, in semi-austenitic precipitation hardening stainless steel [8] as well as the fully austenitic metastable alloys [3]. Type 18-8 stainless steels are typical of the class of alloys which are metastable and fully austenitic at room temperature in the solution annealed condition.

In order to establish some of the factors governing the thermomechanical response of a Type 18-8 stainless steel in the metastable condition, cold work by wire drawing and heat-treatment were varied in this investigation. The primary purpose of this study was to attain strengths of 600 × 10^3 psi. Only two other commercial alloys are known to have achieved this strength level. They are: 0.9% carbon steel, patented wire [9] and AFC 77 stainless steel wire [10, 11].

TABLE I Chemical composition of the stainless steel wire (wt %)

C	Si	Mn	Cr	Ni	Mo	Fe
0.11	1.21	1.27	16.9	8.0	0.74	Bal.

2. Experimental procedure

The material used in this study was a vacuum melted 0.08 in. diameter stainless steel wire supplied by Sandvick Steel, Inc. Chemical analysis is given in Table I. Prior to processing the "mill annealed" wire was solution annealed at 1950°F (~ 1065°C) for 2 sec per mil† of diameter. Except where noted all subsequent anneals were also performed by the same formula. Cold working was done by wire drawing

---

*10^3 psi = 6.89 N mm^{-2}.
†1 mil ≡ 10^{-3} in. = 2.54 × 10^{-5} m.

with standard Brown and Sharp die sequences of 20% reduction of area per pass. The cold work levels reported here are based on the total reduction in area of the wire after its last anneal. Except as noted, the solution annealed 0.08 in. diameter wire was drawn to 84% cold work and divided into four groups. These groups were then annealed at 1400, 1600, 1800 and 1950°F (~ 760, 871, 982 and 1065°C respectively). These temperatures are all above the martensite-austenite reversion temperature and represent a range of recovery and recrystallization behaviour. For each annealing temperature, material was wire drawn to 84, 93.8 and 97.6% cold work. The 1950°F solution annealed wire was additionally cold worked 98.7, 99.4 and 99.6%.

Percent martensite values for the wire drawn materials were determined from a ratio of their measured saturation induction, B_S, to a 100% martensite reference value of 160.4 × 10^2 G determined by Angel [1]. Measurements were made in a field of 10^3 Oe which was determined to be of sufficient strength [12, 13] to virtually saturate the sample. Tensile tests were conducted on an Instron test machine at a 0.01 min^{-1} strain rate.

Elastic modulus measurements were determined by a sonic technique [14] for all the cold worked wires while static measurements were made using a $\frac{1}{2}$ in. Instron extensometer for the annealed wires.

Metallographic examination of the annealed structures revealed that the 1800 and 1950°F materials were fully recrystallized; the 1600°F material was found to be partially recrystallized and the 1400°F material did not recrystallize at all.

3. Results and discussion

True stress-true strain envelopes are shown in Fig. 1 for the 1400, 1600, 1800 and 1950°F annealed and cold worked conditions. The stress data shown are taken at maximum load. For all the cold worked wires, the ultimate tensile strength is equal to the stress at maximum load as they experienced no uniform elongation. The strain data shown represent the cumulative true strain which includes the tensile deformation strain and the wire drawn cold work deformation strain. For the range of strains shown, these data could be fitted to the power law relationship:

$$\sigma = S_1 \epsilon^n \qquad (1)$$

where: σ = true stress, ϵ = true strain, S_1 = material strength constant evaluated at $\epsilon = 1$, n = work-hardening exponent. S_1 was found to decrease with increasing annealing temperature. Conversely, the n values increased with increasing annealing temperature in all cases. The solution annealed condition (1950°F) is seen to give the greatest strengthening at the higher levels of cold work while the least stable conditions (1400 and 1600°F) are seen to give the lowest strengthening. Strengths of up to 540 × 10^3 psi were obtainable in the 1950°F material. At the same time, however, the rate of work hardening appears to decrease rapidly at these strength levels.

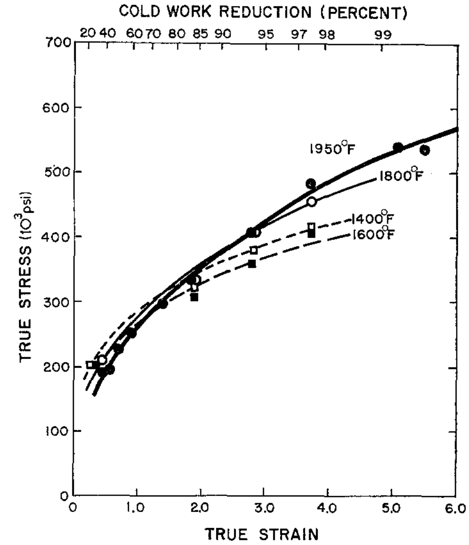

Figure 1 True stress-true strain envelopes constructed from tensile data obtained on the annealed and cold worked wires after annealing at various temperatures.

This decrease in work hardening rate which has been observed in AFC 77 [10, 11] and other ferrous alloys [15] may be due to a dynamic recovery process. The work hardening of metals can be related to the development and refinement of a cellular structure composed of dislocation tangles at the cell walls [9]. The transverse refinement of the cellular structure which results in work hardening may be limited by dynamic recovery process that allows the cell walls to migrate or merge into one another [15]. This type of recovery is seen in many face centred cubic phases (martensite and alpha iron) [15].

It has been shown [9-11, 16] that intermediate heat-treatments can be employed to inhibit dynamic recovery thus preventing decreased rates of work hardening at large deformation strains. Results obtained using an intermediate heat-treatment of 795° F for 4 h are shown for the solution annealed material in Fig. 2. Strengths of 600 to 620 × 10^3 psi were obtained by heat-treating between 97.6 and 99.4% reduction, then continued cold working to either 98.7 or 99.6% cold work followed by a final heat-treatment.

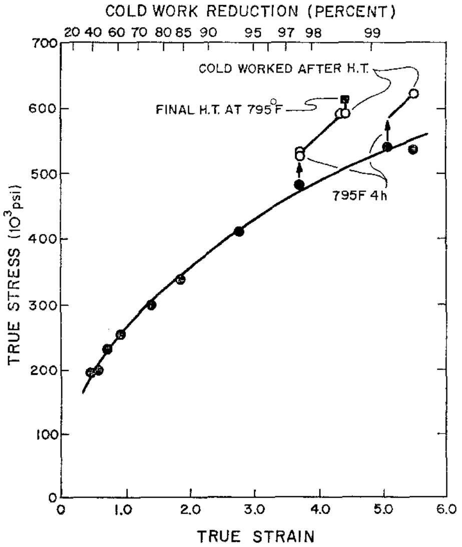

Figure 2 Effect of cold work and intermediate heat-treatments on the work hardening responses for the solution annealed wires (1950° F).

Two effects resulting from the 795° F (~ 424° C) heat-treatment were evident; the first effect as mentioned earlier was to inhibit dynamic recovery; the second effect was to raise the strength level due to an ageing response. A 5 to 10% increase in the amount of martensite transformed was also observed magnetically. This is in agreement with recent observations on thermally induced martensite [17]. Naturally, the contribution of the amount and hardness of the martensitic phase determines the initially high rates of work-hardening and strength levels attained. Subsequent low temperature heat-treatments after transformation to martensite simply enhance any pinning effects due to the carbide precipitation at the cell walls of the dislocation substructure.

The percentage of martensite formed by cold working versus true strain is shown in Fig. 3. A very strong effect of annealing temperature on the amount of martensite subsequently formed can be seen. The largest difference occurs near 84% cold work where the 1950° F material has only 50% martensite compared to the 1400° F material which has approximately 85% martensite. The rate of martensite formation on cold working from the annealed condition increases with decreasing annealing temperature. This is due to an increase in the M_d temperature that occurs with decreasing annealing temperature. Higher M_d temperature scan be expected due to the precipitation of carbides from the austenite at the lower annealing temperatures. At 1950° F most of the carbon goes into solution and results in lower M_d temperatures. The additional carbon in solution from the higher annealing temperatures, while depressing the M_d temperature and thus decreasing the rate of martensite formation, also substantially raises the strength of the martensite. This is apparent in the strength data shown in Figs. 1 and 2. The effect that the amount of martensite plays in developing high strength levels can be observed by plotting strength versus percent martensite at constant levels of cold work. This is shown for the 1950° F annealed material in Fig. 4 where the 100% martensite shows the largest strength increase with increasing cold work. The fully austenitic

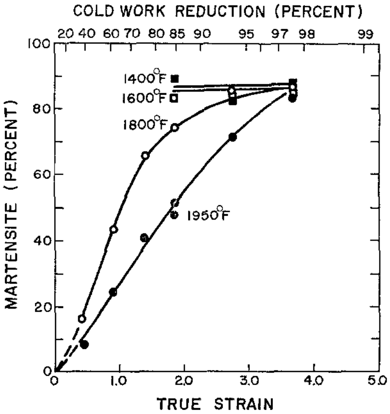

Figure 3 Percent martensite versus true strain introduced by wire drawing for wire annealed at various temperatures.

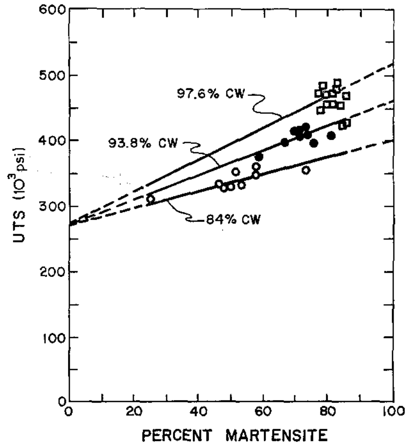

Figure 4 UTS versus percent martensite formed at several levels of cold work for solution annealed wire.

structure has no apparent increase in strength at these strains. Variation in the martensite content was obtained by adjusting the level of cold work before annealing as well as the annealing time. The strength levels shown represent a 0.11 wt % carbon martensite and are not inconsistent with that expected for these levels of cold work [1, 7].

Angel [1] employed an empirical relationship to describe the amount of martensite transformed for a given amount of deformation strain which is:

$$\frac{f}{1-f} = k\epsilon^m \qquad (2)$$

where: f = fraction of martensite transformed, ϵ = true strain, m = transformation exponent, k = constant reflecting the austenite stability. Angel [1] and more recently Ludwigson [18] found m to be a constant of 3 while k varied with chemical composition and test temperature. Where sufficient data were available, similar correlation could be obtained for the 1800 and 1950°F annealed material. These results are shown in Fig. 5. The m value measured for these data was 2 which is lower than the previously reported value of 3 [1, 18]. The reason for this difference is apparently due to the difference in deformation mode. Other investigators [2, 7] have shown that tensile deformation results in a more rapid transformation of martensite over more compressive types of deformation such as wire drawing. In Cina's data [2] this trend for lower m values is also evident for cold rolled stainless steels. It seems reasonable to conclude that m can be varied by varying the mode of deformation.

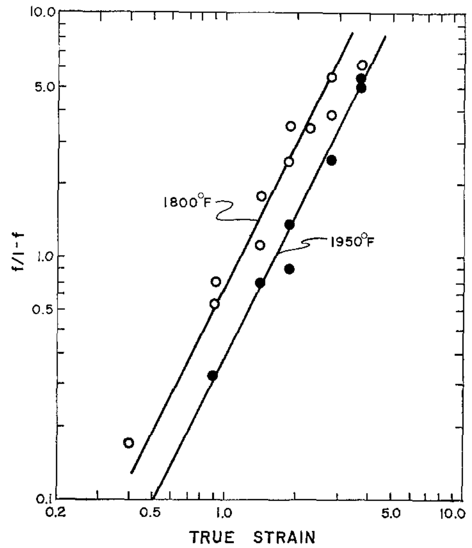

Figure 5 Ratio of the martensite fraction, f, versus true strain introduced by wire drawing after annealing at 1800 and 1950°F.

Elastic modulus data are shown in Fig. 6 versus true strain for the different annealed conditions. The modulus decreases rapidly with increasing strain at the early stages of cold work for the more stable annealed conditions of 1800 and 1950°F. This behaviour has been noted for

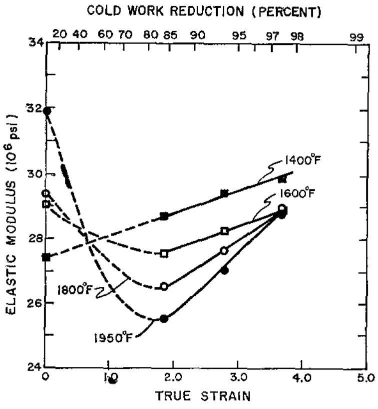

Figure 6 Elastic modulus versus true strain introduced by wire drawing for wire annealed at various temperatures.

metastable as well as stable stainless steels in the austenitic condition [19] and appears to reflect rapid texture development of the austenite. Conversely, the least stable annealed conditions of 1400 and 1600°F do not show as strong an effect due to the rapid martensite formation. At larger strains (above 80% cold work) where the martensite phase predominated, the elastic modulus is seen to increase with increasing amounts of cold work. This trend is naturally more pronounced at very small strains for the least stable condition of 1400°F. For the most stable condition of 1950°C, this behaviour does not develop until 85% work is exceeded.

4. Summary and conclusions

Thermomechanical treatment of metastable austenite using simple annealing, cold drawing and tempering sequences have been employed to achieve tensile strengths of up to 620 × 10^3 psi. These strengths are attainable in Type 18-8 stainless steels provided an optimum solution anneal is used. In this study the optimum anneal appeared to be 1950°F. It has been assumed that (a) the transformed martensite raises the strength level and work hardening rate depending on the amount of martensite and the carbon in solution; (b) a strengthening response occurs which is principally associated with heat-treatment of the cold worked martensite and the thermally induced formation of martensite.

Tensile strengths exceeding 500 × 10^3 psi were obtainable directly by deformation hardening which appeared to dissipate due to a dynamic recovery process at the larger cold work reductions exceeding 98%. This form of recovery could be inhibited by introducing intermittent heat treatments at 795°F for 4 h. This heat-treatment tended to strengthen the wire as well as inhibit recovery. Cold working to 98.7% with the intermittent heat-treatments provided the most dramatic increase in strength of over 600 × 10^3 psi.

The hardness as well as the amount of martensite formed was shown to be strongly influenced by the prior annealing temperature. The most stable condition appeared to be the 1950°F solution anneal which resulted in the hardest martensite as well as the lowest M_d temperature. The least stable condition was for the 1400°F anneal due to the precipitation of carbon from solution. This resulted in high M_d temperatures and a relatively soft martensite.

It was also shown that for wire drawing the volume fraction of martensite formed is directly related to the square of the deformation strain. Previous work [1] had shown this to be related to the cube of the strain using tensile deformation.

The elastic modulus was also shown to be sensitive to the relative stability of the stainless steel. The least stable conditions resulted in gradual increases in modulus with increased cold work. Conversely, the most stable conditions result in a rapid decrease in modulus initially with increasing cold work. Later on at higher levels of cold work this trend is reversed and the modulus tends to increase.

Acknowledgements

The authors wish to express their appreciation to Brunswick Corporation for permission to publish this work; and to acknowledge the assistance of J. Quirk who did the wire drawing and heat-treatments and Ann Norcott who did the elastic modulus measurements. We would also like to acknowledge the contribution of Dr J. Roberts and R. Owen who developed the experimental procedures used to determine the magnetic saturation induction values. Finally, we would like to acknowledge the contribution of Sandvick Steel, Inc, who donated the stainless steel used in this study.

References

1. T. ANGEL, *J. Iron Steel Inst.* **177** (1954) 165.
2. B. CINA, *ibid* **177** (1954) 406.
3. K. M. CARLSEN and K. C. THOMAS, *ASM Trans. Quart.* **55** (1962) 462.
4. S. FLOREEN and G. W. TUFFNELL, *ibid* **57** (1964) 301.
5. E. B. KULA, Proceedings of the Twelfth Sagemore Army Materials Research Conference on Strengthening Mechanisms, edited by J. J. Burke, N. L. Reed and V. Weiss (Syracuse University Press, 1966) pp. 83-122.
6. J. C. SHYNE, F. W. SCHALLER and V. F. ZACKAY, *ASM Trans. Quart.* **52** (1960) 848.
7. H. JARLEBORG, *Wire and Wire Products*, January (1966) 80.
8. A. F. HOENIE and D. B. ROACH, DMIC Report 223, Battelle Memorial Inst., Columbus, Ohio (1966).
9. J. D. EMBURY and R. M. FISHER, *Acta Metallurgica* **14** (1966) 147.
10. V. K. CHANDHOK and A. KASAK, AFML-TR-67-308 (1967).
11. *Idem, Metal. Prog.*, January (1967) 108.
12. F. BRAILSFORD, "Physical Principles of Magnetism", (Van Nostrand, London, 1966) p. 274.

13. R. M. BOZORTH, "Ferromagnetism" (Van Nostrand, Princeton, 1951) p. 968.
14. J. NUNES and W. KLEIN, *ASM Trans. Quart.* **60** (1967) 726.
15. G. LANGFORD and M. COHEN, *Trans. ASM* **62** (1969) 623.
16. W. HODGE, R. I. JAFFEE J. G. DUNLEARY and H. R. OGDEN, *Trans. Met. Soc. AIME* **180** (1949) 15.
17. P. L. MANGONON, JUN and G. THOMAS, *Met. Trans.* **1** (1970) 1587.
18. D. C. LUDWIGSON and J. A. BERGER, *J. Iron Steel Inst.* **207** (1969) 63.
19. R. P. MIKESELL and R. P. REED, *J. Res. Nat. Bur. Stand.* **70C** (1966) 207.

Received 6 August and accepted 16 October 1974.