Influence of chromium on superplasticity in ultra-high carbon steels

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The influence of chromium additions to ultra-high carbon steels has been investigated. A common bearing steel (52100 containing 1% C and 1.5% Cr), a 1.6% + 1.5% Cr steel (designated 52160) and a plain 1.6% C steel have been compared. Chromium is found to enhance greatly the superplastic properties. This is because the chromium enters the cementite and thereby stabilizes it. This in turn allows very little grain growth in ferrite to occur during superplastic deformation. A value of 1220% elongation to failure in 52160 was found at 650° C at an initial engineering strain rate of 1% min^{-1}. The influence of strain rate on the elongation to failure has also been investigated in this material.

1. Introduction

It is now well established [1–3] that steels containing between 1% C and 2% C can readily be processed to possess an attractive combination of properties at both warm (0.5 to 0.65 T_m) temperatures (i.e. superplasticity) and at room temperature. This paper describes results concerning the influence of small additions (~ 1.5%) of chromium.

Ultra-high carbon (UHC) steels are processed into a fine-grained form by any one of five routes [3]. The final structure in all cases is one of extremely fine cementite particles (0.1 to 0.5 μm) in a matrix of fine-grained ferrite (0.5 to 2 μm). Chromium is known to act as a carbide stabilizer entering the cementite, up to 9 wt %, to form a complex carbide $(Fe, Cr)_3C$ [4, 5]. It was believed that this improved stability, through small chromium additions, should improve the warm temperature superplastic properties and also the room temperature properties of UHC steels. Three steels were used for this investigation. The first was a plain 1.6% C steel. The second was a commercial 52100 bearing steel (nominal composition 1% C, 1.5% Cr) and the third was a specially prepared high carbon modification of 52100 which, for convenience, we designate as 52160 (nominal composition 1.6% C, 1.5% Cr). Increasing the carbon content in the low alloyed steel increases the volume fraction of cementite and this leads to the prevention of ferrite grain growth during superplastic flow. All three steels were prepared by vacuum melting and their compositions are given in Table I.

2. Experimental procedure

Ultra-high carbon steels in the as-cast condition normally have a coarse pearlitic structure with pro-eutectoid cementite at the grain boundaries. Both the 52160 steel and the 1.6% C steel were received in this condition (courtesy of Jones and Laughlin Steel Co.) and an example is shown in Fig. 1. The commercial 52100 bearing steel,

TABLE I Composition of UHC steels investigated (wt %)

Steel	C	Cr	Mn	Si	S	P	Ni	Cu	Ti	Fe
52100	1.005	1.42	0.41	0.28	0.001	0.01	0.15	0.12	–	Balance
52160	1.640	1.61	1.00	0.22	0.006	0.01	0.07	0.01	0.01	Balance
1.6C	1.600	0.02	1.03	0.21	0.006	0.01	0.07	0.01	0.01	Balance

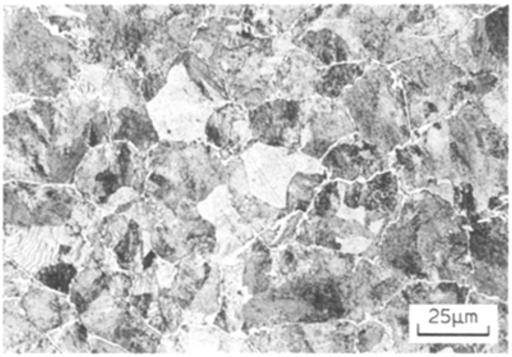


Figure 1 Optical photomicrograph of 52160 steel in the as-received condition.

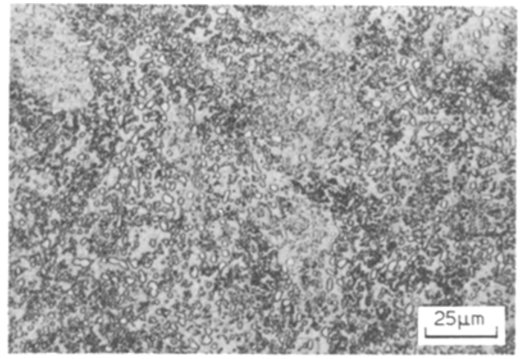


Figure 2 Optical photomicrograph of 52100 steel in the as-received condition.

however, was purchased in the spheroidized condition. In this case, Fig. 2, fairly coarse cementite particles of size 1 to 2 μm are in a ferrite matrix of grain size $\sim 12\,\mu$m.

These three steels were processed by a combination of hot and warm rolling. Initially, small blocks of the steels (measuring 25 mm x 38 mm x 125 mm) were solution treated at 1100° C for about 1.5 h. At this temperature all the carbon should be in solution [6]. The steels were then rolled during cooling from 1100° C through the γ and $\gamma + Fe_3C$ ranges and just into the $\alpha + Fe_3C$ range. The steels were rolled at about 10% per pass and a true strain of $\gtrsim -1.5$ was achieved. This was followed by isothermal rolling in the $\alpha + Fe_3C$ range, at 650° C, at 10% per pass, until a true strain of greater than -1 had been reached. The final product was a sheet of about 2.5 mm thickness. Details of the thermomechanical processings are shown in Table II.

Using tensile coupons machined from final rolled strip, superplastic properties were evaluated by measuring the elongations to failure during tensile testing at 650° C in an atmosphere of forming gas. Tests were also carried out to determine the strain rate sensitivity, m, at 650° C by measuring the flow stress at each of a number of imposed strain rates.

Samples for metallographic examination were prepared in the normal way and nital was used as an etchant. Grain sizes were determined from optical micrographs. The mean linear intercept, $\bar{L}$, was measured and converted to the average spatial grain diameter, D, using the relationship $D = 1.75\,\bar{L}$ [7].

3. Results and discussion

The results of the tests are summarized in Fig. 3. All three steels were found to be superplastic, i.e. m values were in the range $0.3 < m < 0.6$ and elongations to failure were high. For example, at an engineering strain rate, $\dot{e}$, of $1\%\,\mathrm{min}^{-1}$, elongations to failure of 470%, 330% and about 1200% were found for the 1.6% C steel, the 52100 steel and the 52160 steel respectively. It was noted that the 52160 material exhibits a higher elongation than does the plain 1.6% C material despite having a lower measured value of strain rate sensitivity. The work of Ghosh and Ayres [8] would suggest that this probably reflects the fact that it is the terminal strain rate sensitivity that controls elongation at fracture. That is, the strain rate sensitivity near fracture, and not the one measured in the conventional manner where "m" is typically determined over the first 100% elongation.

TABLE II Thermomechanical processing

Steel	True strain, ϵ, during working from 1100° C to ~650° C	True strain, ϵ, during isothermal rolling at 650° C	Total strain
52100	$\epsilon = -1.81$ in 19 passes	$\epsilon = -1.15$ in 24 passes	-2.96
52160	$\epsilon = -1.48$ in 15 passes	$\epsilon = -1.35$ in 18 passes	-2.83
1.6% C	$\epsilon = -1.71$ in 16 passes	$\epsilon = -1.15$ in 13 passes	-2.86

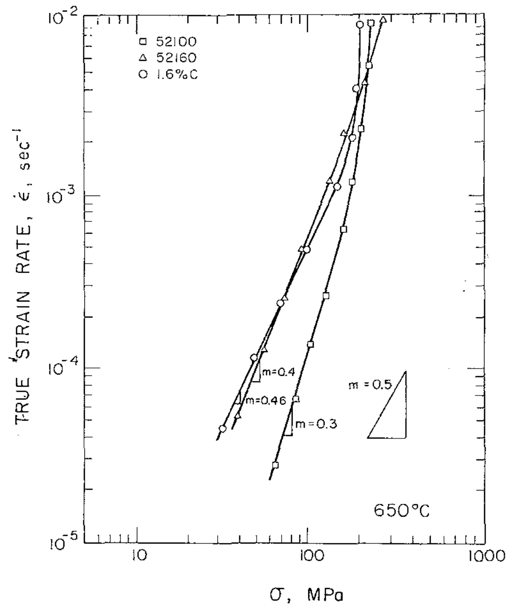


Figure 3 Determination of the strain rate sensitivities of the three steels at 650° C as assessed by measuring the flow stresses at each of a number of imposed strain rates.

The 52100 steel (Fig. 3) shows a low value of strain rate sensitivity ($m = \sim 0.3$). We attribute this result to the presence of a mixture of low and high angle boundaries in 52100 after extensive warm temperature deformation. This fits in well with Kayali's observation [9] that, when the carbon content is high (e.g. eutectoid composition) but not ultra-high, the result of warm processing is to obtain a mixed structure of low and high angle boundaries. The low angle boundaries in this mixture cannot fully contribute to superplastic flow and hence marginal superplastic properties result. They can readily be removed by a simple cycling heat treatment. This involves taking the steel to a temperature just above the $\gamma \rightarrow \alpha$ transformation (~723° C). At this temperature the low angle boundaries are transformed to high angle ones and on cooling retain their high angle nature. Thus upon testing at 650° C improved superplastic properties result. This is the case for 52100 where, after cycling, an m value of 0.48 and an elongation to failure of 730% were found [10, 11].

An elongation to failure value of about 1160% was found in the case of 52160 as shown in Fig. 4. In a repeat test, for material for metallographic examination, a value of 1220% was recorded. This is the first time in the brief history of these materials that values in excess of 1000% have been achieved. These high values for 52160 are attributed to the beneficial influence of the increased quantity of cementite through increasing the carbon content (cf. 52100), and to the improved stability of the cementite through the chromium additions (cf. 1.6% C steel).

This conclusion is supported by metallographic observation of the three steels. The 52160 steel is shown in Fig. 5 in the as-rolled and as-deformed (to about 200%) conditions. Also shown is the specimen head which experienced no strain and hence effectively has been annealed. Grain growth was found to be a minimum for the 52160 material. In 52160 material, even after 1000% deformation, grain growth is from submicron size in the as-rolled condition to about only 3 μm (Fig. 5). By comparison, the plain ultra-high carbon steel and the 52100 exhibit grain growth more rapidly although even in these cases the final grain size does not exceed 4 to 5 μm.

Because of the high elongations found, and the retention of a good strain rate sensitivity at high strain rates, Fig. 3, 52160 was tested over a wide range of strain rates (0.4% to 1000% min^{-1}) at 650° C. The results are shown in Fig. 6 and reflect the extremely high formability of this material in the fine grained condition over a wide range of strain rates. Thus, at 100% min^{-1} the tensile ductility was 330% and at 1000% min^{-1} it was an impressive 131%. A maximum elongation of 1220% is found at 1% min^{-1}. At the very lowest strain rate (0.4% min^{-1}) the elongation to failure decreases to 750%. This is due to the prolonged time and hence grain growth at the testing temperature.

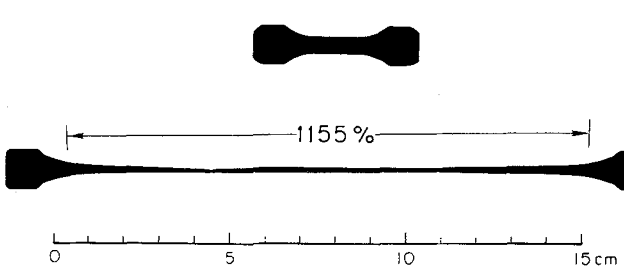
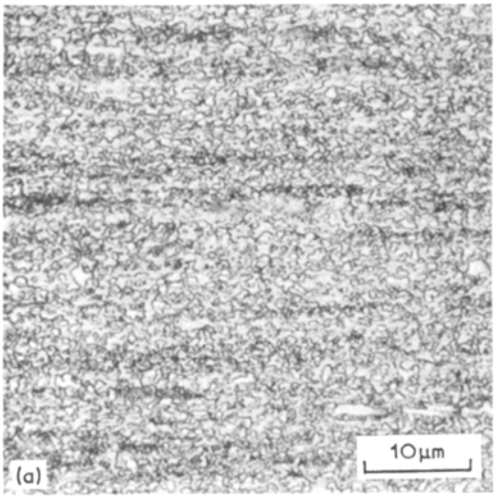
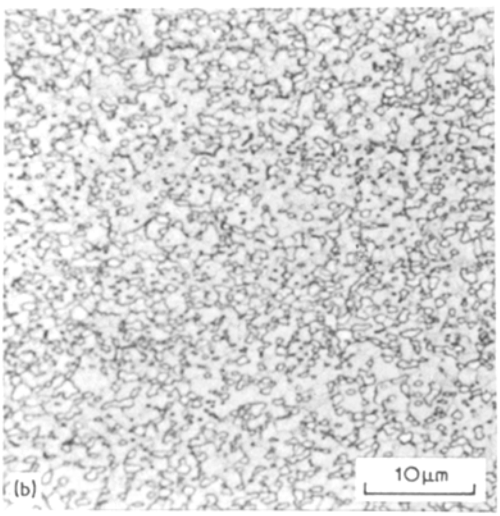
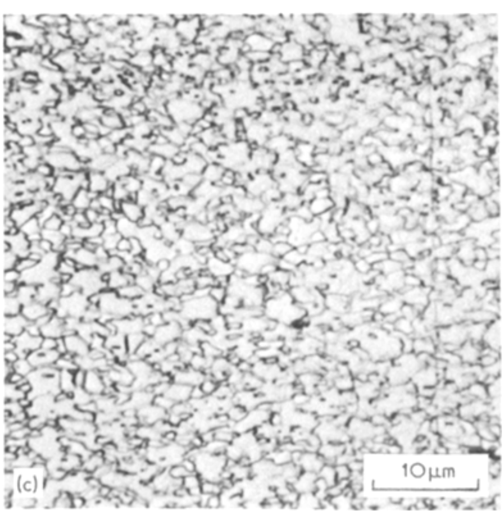


Figure 4 52160 steel tested to failure in tension at 650° C at a strain rate of 1% min^{-1}.







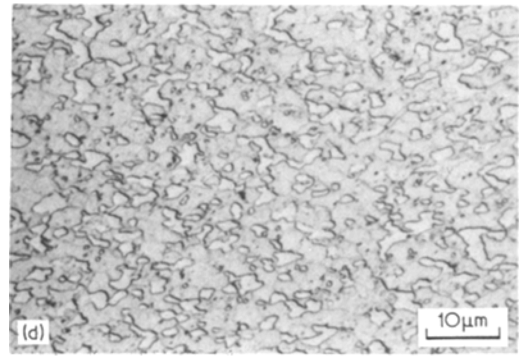


Figure 5 Optical photomicrograph of 52160 steel. (a) As hot and warm rolled; (b) undeformed head of specimen tested at 650° C; (c) gauge section of specimen tested at 650° C; (d) gauge section of specimen tested to over 1000%.

Room temperature properties of these materials have also been assessed and are summarized in Table III. These values represent the averages of several tests. Materials were tested in the as-rolled condition and also after an annealing treatment at 650° C for 20 min. Specimens were tested in tension on an Instron machine at an initial engineering strain rate of 2% $\min^{-1}$. The room temperature properties are seen to be impressive for all three steels, high strengths (~900 to 1000 MPa) with good ductilities recorded in all cases. Chromium is seen to have a beneficial effect upon room temperature strength reflecting the influence of chromium on refinement of the grain size and carbide size. Annealing considerably improves ductility, by a factor of about two, at the expense of a small decrease in strength.

4. Conclusions

The addition of chromium has a significant, beneficial influence on UHC steels that already possess a unique and attractive combination of warm temperature formability with high strengths and good ductility at room temperature.

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TABLE III Room temperature properties

Steel	As-rolled			As-rolled + annealed at 650° C		
	Yield point (MPa)	Ultimate tensile strength (MPa)	Per cent elongation (in one in.)	Yield point (MPa)	Ultimate tensile strength (MPa)	Per cent elongation (in one in.)
52100	925	1021	11.9	883	945	18.7
52160	1028	1159	6.4	994	1090	11.7
1.6% C	897	974	8.6	835	856	18

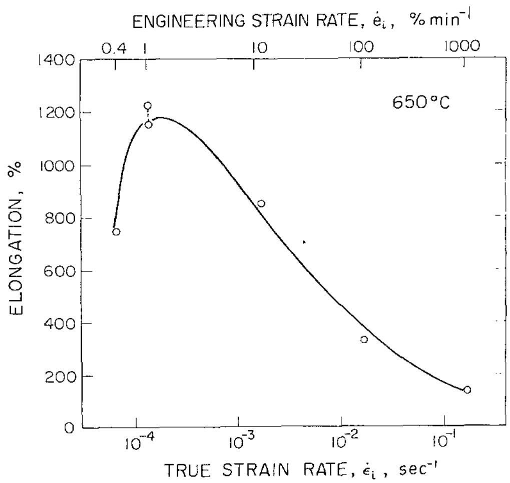

Figure 6 Elongation to failure as a function of strain rate for 52160 steel at 650° C.

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