THE EFFECT OF CARBIDE MORPHOLOGY ON THE FRACTURE OF NICKEL-BASE ALLOYS

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The effect of carbide morphology on the room temperature tensile properties of commercial alloys and experimental Ni-Fe alloys containing chromium, molybdenum, niobium or tungsten has been investigated. Grain and twin boundary carbides found in chromium- and molybdenum-containing alloys reduced ductility to low levels. Niobium and tungsten additions led to the formation of only intragranular carbides which enabled high room temperature ductilities to be retained at high carburization levels.

INTRODUCTION

In many high temperature applications, metallic materials are subjected to aggressive environments containing carbonaceous gases such as methane and carbon monoxide which can lead to extensive carburization. The diffusion of carbon into the alloy followed by precipitation of carbides in the matrix significantly affects the mechanical behaviour, especially strength and toughness at low and intermediate temperatures. For protection against carburization, a compact oxide film is required which prevents the ingress of carbon from the atmosphere.

In specific cases, it is difficult to guarantee the formation of oxide films necessary for carburization resistance due to a low oxygen potential. This applies to the primary coolant helium of a high temperature reactor, the helium containing traces of methane, carbon monoxide, hydrogen and water, in the µbar range.

In order to assess the significance of carbon uptake in HTR candidate high temperature alloys, the effect of carbon content on the room temperature tensile properties and on the impact strength at 20 - 800 °C has been determined. In addition, as an initial step towards the development of alloys more resistant to the embrittling effects of carbide precipitation, a range of experimental alloys based on Ni-Fe with ternary additions of the carbide-forming elements chromium, molybdenum, niobium and tungsten was prepared. The effect of carbide morphology on room temperature tensile properties was investigated using these alloys.

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RESULTS

Commercial alloys

In the first part of the work, the two commercial alloys, INCONEL 617 (Ni - 22 Cr - 9 Mo - 12,5 Co - 1 Al) and INCOLOY 800 H (Fe - 32 Ni - 20 Cr) were carburized using various gas mixtures. The results of room temperature tensile tests have been published by Ennis and Lupton (1) and Ennis and Schuster (2). It was found that the rupture elongation decreased sharply with increasing carbon content, as shown in Figure 1. There was, however, a difference in the ductility-carbon content relationship for the two alloys, in that the iron-base INCOLOY 800 H contained twice as much carbon than the nickel-base INCONEL 617 for similar ductilities. This was attributed to

- higher solubility of carbon in the Fe-Ni-Cr matrix than in the Ni-Cr-Mo matrix
- the formation of M_6C in INCONEL 617 in addition to $M_{23}C_6$; in INCOLOY 800 H, only $M_{23}C_6$ is found at carbon contents below about 1 %.

Figure 2 summarizes the impact properties of carburized INCONEL 617 and INCOLOY 800 H; again carburization produces a decrease in toughness but it should be noted that for INCONEL 617, thermal treatment alone also causes a sharp decrease in toughness.

Metallographic examination showed that carbide precipitation at grain and twin boundaries is responsible for most of the ductility loss. Figure 3 shows a section through the fracture face of an INCONEL 617 impact test piece after carburization to a bulk carbon content of 0.21 wt. % and testing at 20 °C. The fracture follows the carbide precipitates on grain boundaries, and cracks have formed in primary carbides.

Experimental alloys

The compositions (see Table 1) were selected to produce different carbides and carbide morphologies after carburization. Metallographic examination of the carburized alloys showed that the alloys could be divided into two groups. The chromium- and molybdenum-containing alloys formed predominantly grain-boundary carbides, and in the alloys containing niobium or tungsten, intragranular, finely dispersed carbides were formed.

Table 1 - Analysed compositions (wt %) of experimental alloys

Alloy	C	Ni	Fe	Cr	Mo	W	Nb
1.	0.024	63.7	16.1	20.1	-	-	-
2.	0.032	74.5	19.0	6.4	-	-	-
3.	0.035	72.5	18.9		8.5	-	-
4.	0.026	76.1	18.9	-	-	14.5	-
5.	0.026	76.1	18.9	-	4.9	-	-
6.	0.029	77.9	20.1	-	-	-	1.9

The room temperature tensile properties are plotted in Figure 4 as a function of carbon content. The chromium-containing alloys showed similar behaviour to the commercial alloys, but the niobium- and tungsten-containing alloys retained high rupture elongation at carbon levels of around 1 %, due to the dispersed intragranular carbide and the absence of grain boundary precipitation.

Figure 5 compares the microstructures after tensile testing, showing the distribution and the fracture of the carbides in the microstructure. In the chromium-containing alloy the grain boundary carbides which are parallel to the strain direction fracture into approximately equal lengths until the maximum stress in the remaining carbide pieces falls to below the fracture stress of the carbide. Carbides aligned perpendicularly to the strain direction separate along their length, the crack occurring only in the carbide and not at the carbide-matrix interface. Rupture occurs when the cracks in the carbides on transverse grain boundaries link up (Figure 5 a). In the tungsten-containing alloys, the carbides also fracture but there remains a large volume of ductile matrix between the cracked carbides (Figure 5 b). Eventual failure occurs by ductile fracture of the matrix.

DISCUSSION

The results of room temperature tensile tests have shown that modifying the carbide morphology from grain and twin boundary films as in commercial high temperature alloys containing chromium and molybdenum to finely dispersed intragranular particles significantly increases room temperature ductility which can be achieved in heavily carburized material. The addition of tungsten or niobium allow this modification of carbide morphology due to their low diffusivity in the nickel matrix.

In the development of materials for the HTR, corrosion tests in various simulated service environments carried out by Dean and Ennis (3) have indicated that it may be beneficial to reduce chromium content and rely on stronger oxide formers such as titanium to provide carburization resistance. The loss of high temperature strength due to the lowering of the chromium and molybdenum contents can be compensated for by the addition of other solid-solution hardening elements, and Dean (4) showed from theoretical considerations of strengthening effects that tungsten and niobium appeared the most favourable elements. The present work on the model alloys suggests that these compositional modifications to produce better corrosion resistance in simulated HTR helium will also lead to improved ductility after carburization.

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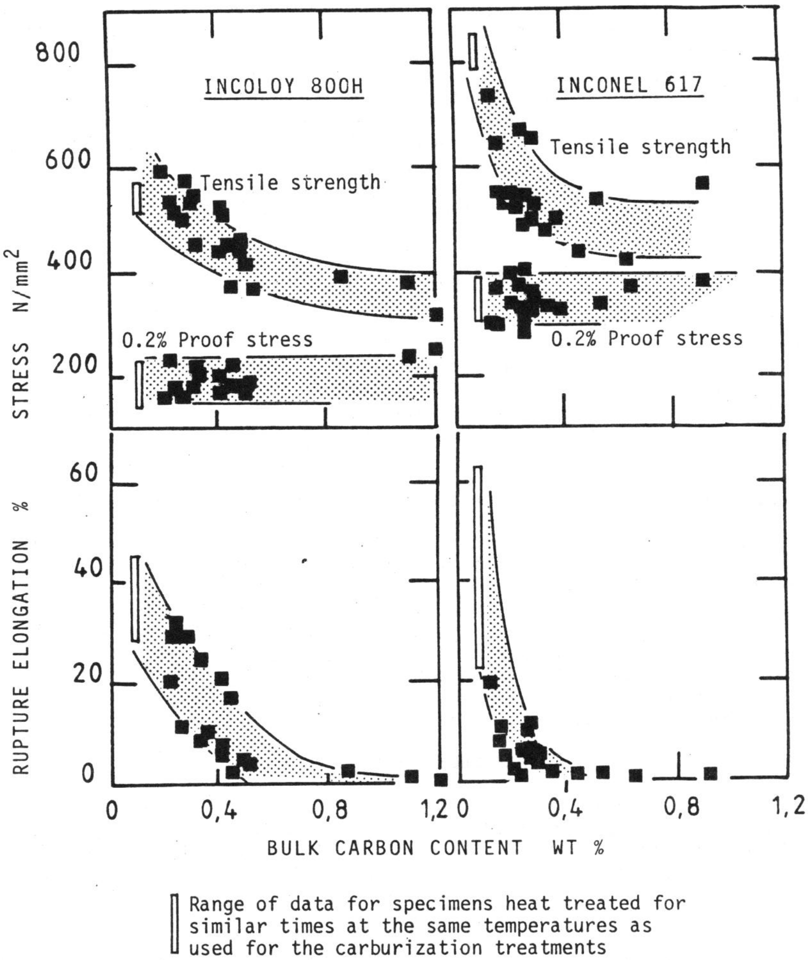


Figure 1 Room temperature tensile properties of carburized INCOLOY 800H and INCONEL 617

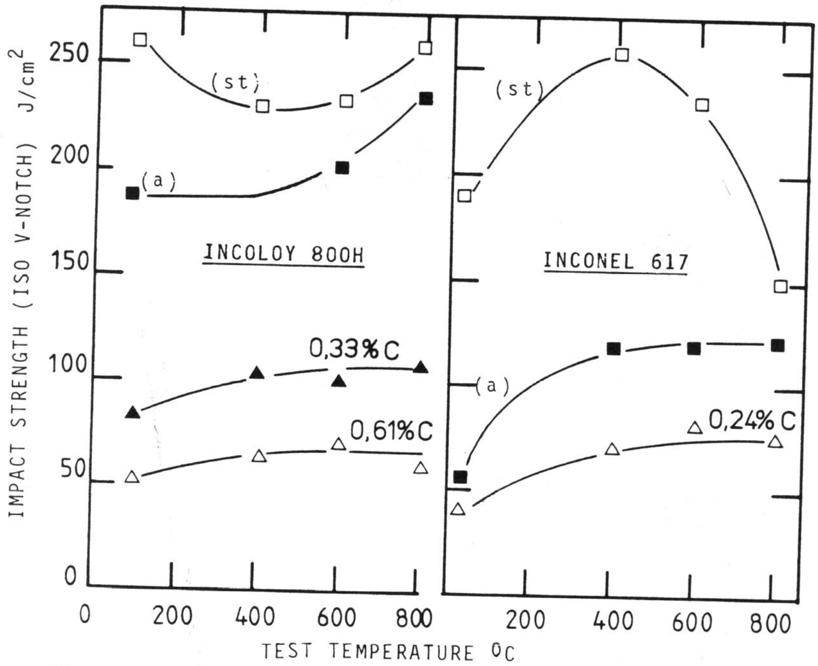
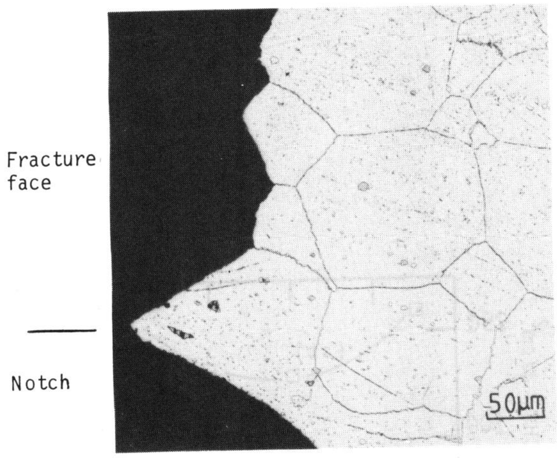


Figure 2 Impact strength of INCOLOY 800H and INCONEL 617 in the solution treated condition (st), after ageing for 100, 250 and 500 hours at 850^{0}C (a) and after carburization at 850^{0}C (bulk carbon content in wt % given)

Figure 3 Microstructure of INCONEL 617 carburized to bulk carbon content of 0.2 wt % and tested at room temperature.



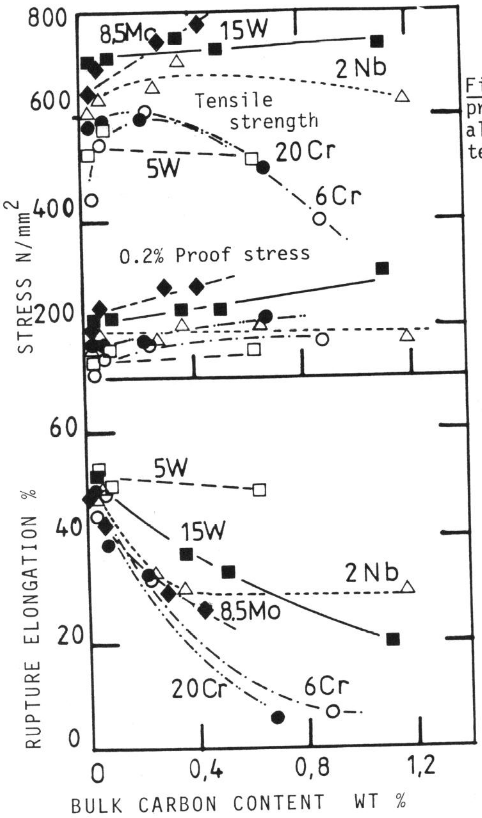


Figure 4 Room temperature tensile properties of carburized Ni-Fe alloys containing Cr, Mo, Nb or W: ternary addition given in wt %.

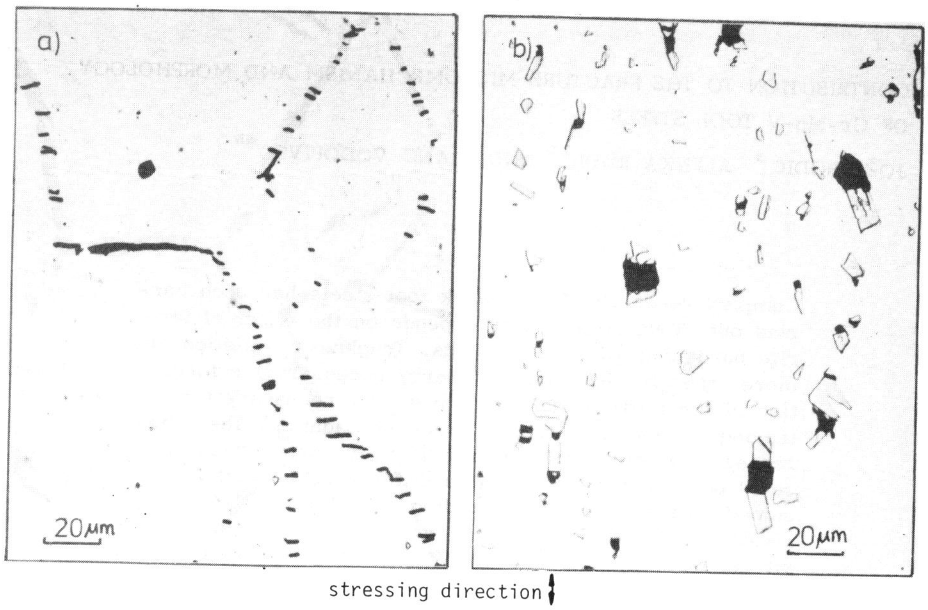


Figure 5 Microstructures of carburized Ni-Fe alloys after tensile testing at room temperature: a) Ni-16Fe-20Cr, carbon content 0.7 wt %
b) Ni-16Fe-15W, carbon content 0.5 wt % .

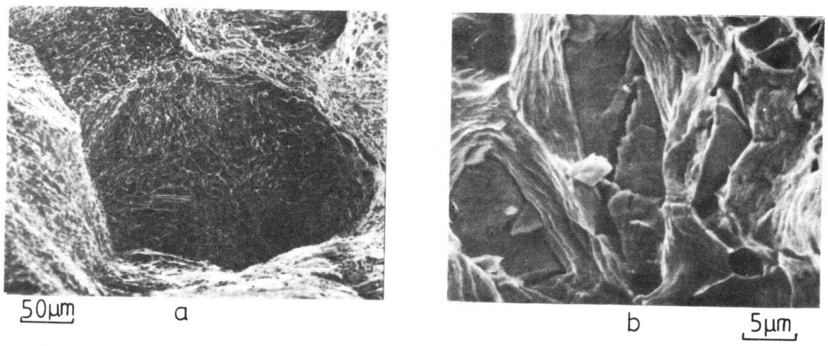


Figure 6 Fracture surfaces of carburized Ni-Fe alloys after room temperature tensile testing: a) Ni-16Fe-6Cr, carbon content 0.88 wt %
b) Ni-16Fe-15W, carbon content 0.5 wt %