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Effect of Carbon on Microstructure and Mechanical Properties of a Eutectoid β Titanium Alloy

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The influence of carbon addition on the aging response of quenched Ti-13wt.%Cr has been investigated using hardness tests, tensile tests, optical microscopy, scanning electron microscopy, and transmission electron microscopy. The addition of carbon improves the homogeneity of α precipitation, reduces the growth rate of α, and greatly reduces grain boundary α precipitation. The carbon addition accelerates the rate at which hardening occurs during aging, increases the peak hardness of aged samples, and also increases the room temperature tensile strength and ductility of aged samples. The factors giving rise to the improvements in properties will be discussed in terms of the microstructural observations.

Keywords age-hardening, βTi alloys, carbon

1. Introduction

It has been shown that the addition of C to Ti-25V-15Cr-2Al alloy leads to a significant improvement in the ductility of this alloy, which is reduced to close to zero when it is exposed at 550 °C for 500 h, but with 0.2 C added the ductility is more than 10% (Ref 1). The improvement comes about because the Ti_2C that is formed acts as a getter, and reduces the oxygen content in the matrix alloy and in the grain boundary regions. This reduction of oxygen in the grain boundary region is important because it reduces the embrittling precipitation of α at the operating temperature of about 550 °C. In addition, the carbides limit grain growth during processing. It has been shown that the formation of Ti_2C is a necessary, but not a sufficient, condition for the carbide to act as a getter (Ref 2). It is also necessary that oxygen has significant solubility in the Ti_2C, and this has been found to be the case for alloys containing V, Mn, Fe, and Cr (Ref 2, 3).

The present work has been undertaken in an attempt to distinguish between the roles of the carbides themselves and the oxygen content in the matrix in influencing the kinetics of the precipitation of α. The presence of the hard carbides leads to dislocation generation during quenching as well as to internal stress, and these dislocations act as sites for α precipitation (Ref 4). The reduction in oxygen may by itself influence the nature of α precipitation because, although it is an α stabilizer, its role on ω precipitation (which can act as a precursor for α precipitation) (Ref 5-7) may be important.

2. Experimental

One kilogram buttons of Ti-13Cr, with and without the addition of 0.15 C, were melted using elemental feedstock in a plasma melter. Buttons were melted at least four times to ensure chemical homogeneity. The oxygen content in both the C-free and the C-containing samples was 900 ppm. Four volume percent of yttria particles were added to one button of the C-free alloy. Sections from the buttons were forged at 1050 °C at a strain rate of 5×10^{-3}/s to break down the cast structure and samples cut from these buttons were solution-treated at 950 °C for 2 h and water-quenched. Samples were aged at 400, 450, 500, and 600 °C for times up to 64 h for hardness tests. Samples for tensile tests were aged for 2 h at 400, 500, and 600 °C. A microstructural assessment using optical, scanning electron microscopy (SEM), and transmission electron microscopy (TEM) has been carried out on the as-quenched and aged samples.

3. Results and Discussion

3.1 Hardness Results and Tensile Data

Figure 1 shows the aging response for aging times up to 8 h for the C-free and C-containing samples in which it can be

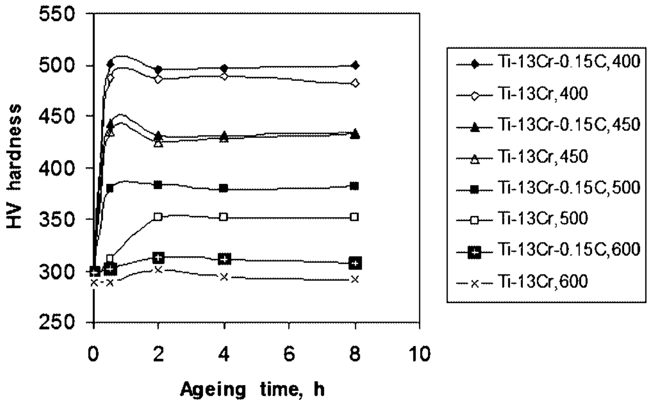

Fig. 1 Age-hardening response of Ti-13Cr and Ti-13Cr-0.15C aged for the times and temperatures indicated. The influence of C is clearly largest for the samples aged at 500 °C.

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seen that in all cases, apart from the curves corresponding to an aging temperature of 450 °C, more rapid aging and a higher final hardness in the C-containing samples can be seen. The most significant effect is found for an aging temperature of 500 °C. The early stages of hardening involve an obvious decrease for all temperatures other than 600 °C.

Figure 2 shows the aging response at 400, 500, and 600 °C for times up to 64 h, and, again, it is clear that the addition of carbon increases the aging response, although the benefits are not as significant as those reported in Ti-15-3. Nevertheless, for aging at 500 °C the peak hardness is significantly higher in the C-containing alloy and is maintained for much longer times than in the C-free alloy. Thus, for both short and long aging times (most obvious at 500 °C) the addition of carbon increases the kinetics of aging, and also increases the maximum hardness reached and the aging time for which this hardness is retained.

The room temperature tensile properties are shown in Table 1 for samples aged at 400, 500, and 600 °C for 2 h. The

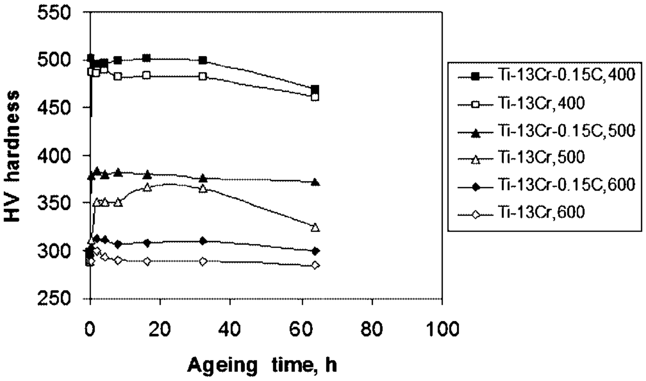

Fig. 2 Age-hardening response of Ti-13Cr and Ti-13Cr-0.15C aged for times up to 64 h at the temperatures indicated

Table 1 Tensile properties of Ti-13Cr with and without the addition of 0.15 wt.% C after quenching from 950 °C and ageing for the times and temperatures indicated

Alloy	Heat treatment	0.2% proof stress, MPa	UTS, MPa	Elongation, %
Ti-13Cr	400 °C 2 h	917	1130	0.8
Ti-13Cr-0.15C	400 °C 2 h	1036	1195	1
Ti-13Cr	500 °C 2 h	1066	1143	1.2
Ti-13Cr-0.15C	500 °C 2 h	1182	1207	6.2
Ti-13Cr	600 °C 2 h	869	869	1.1
Ti-13Cr-015C	600 °C 2 h	929	930	6.8

Note: UTS, ultimate tensile strength

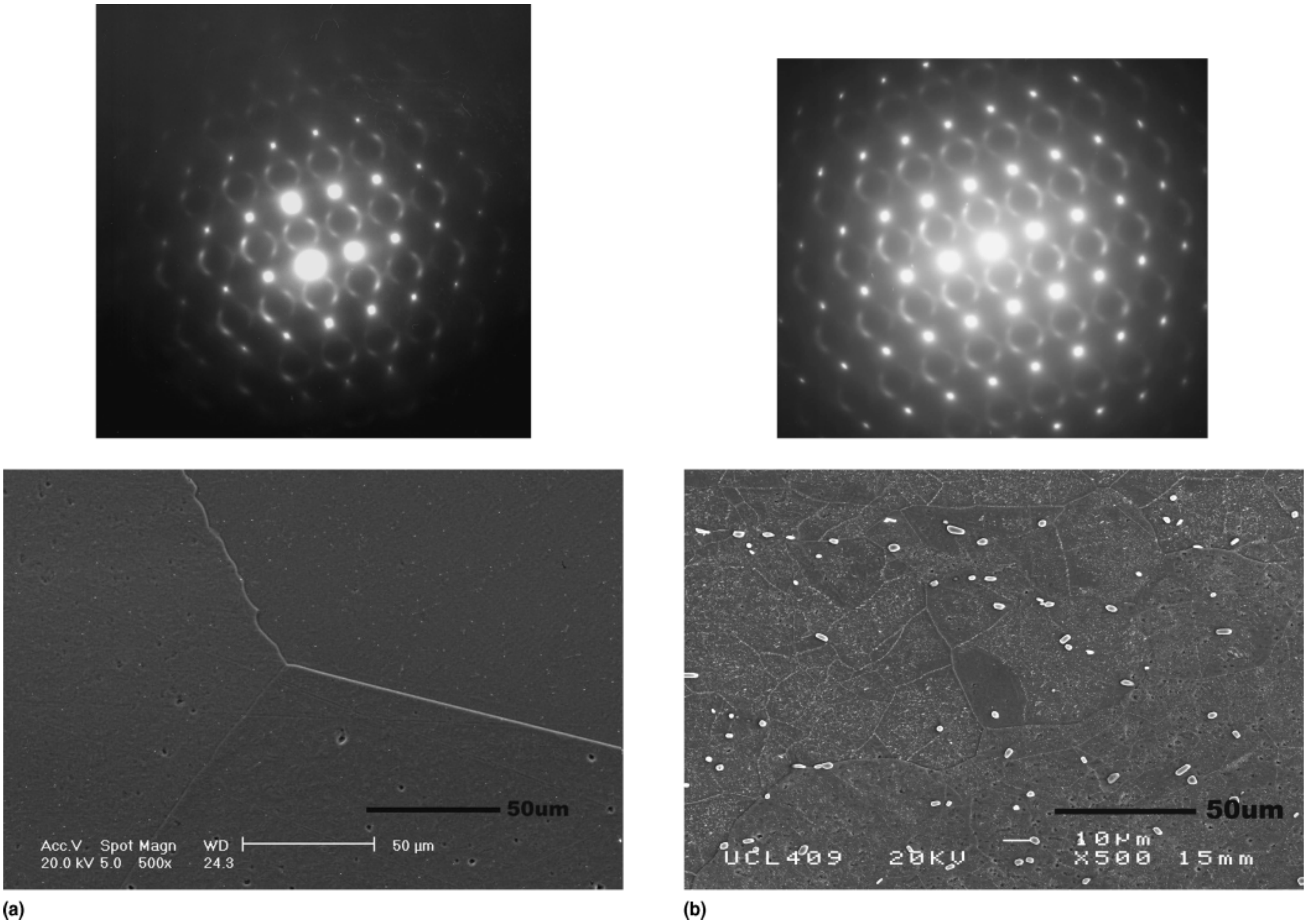

Fig. 3 Secondary electron micrographs and transmission electron diffraction patterns from as-quenched samples of Ti-13Cr: (a) C–free sample; (b) C-containing sample

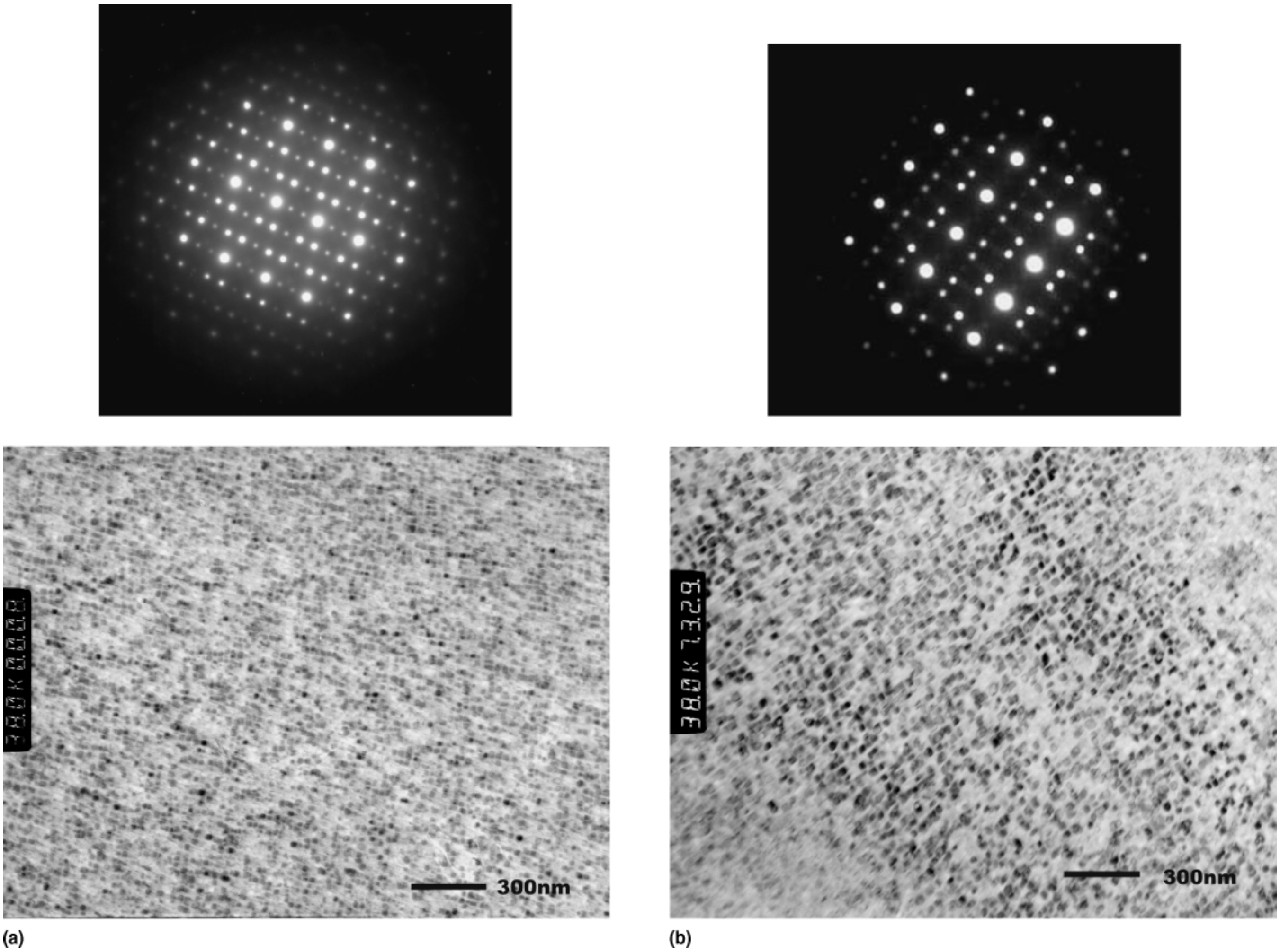

Fig. 4 Many beam TEM images showing ω precipitates and corresponding diffraction patterns in Ti-13Cr quenched from 950 °C and aged for 2 h at 400 °C: (a) C-free sample; (b) C-containing sample

ductility is improved for all aging conditions in the C-containing samples with all C-free samples showing ductilities of about 1%; the effect of the C addition on the ductility is minimal for a 400 °C aging temperature. The best balance of properties is obtained in the C-containing samples aged at 500 °C.

3.2 Microstructural Observations

Figure 3(a) and (b) show SEM images of the as-quenched samples of Ti-13Cr, Ti-13Cr-0.15C, and corresponding diffraction patterns obtained using TEM. These micrographs show that the carbides, which are obvious in Fig. 3(b), reduce the grain size significantly. In both alloys, the diffraction patterns show extra reflections due to ω.

Figure 4(a) and (b) show TEM images and their corresponding diffraction patterns obtained from samples of Ti-13Cr with and without C after aging for 2 h at 400 °C. It is clear that the ω reflections are now even more pronounced, and ω precipitates can be seen in both micrographs. The cubic precipitates visible both in Fig. 4(a) and (b) are typical of ω precipitates in Ti alloys with a large misfit (Ref 8), and there appears to be a similar density of these precipitates in the C-free sample and the C-containing sample. The low ductility observed in samples aged at 400 °C is presumably associated with the high density of ω.

Figure 5(a) and (b) show SEM images from samples aged for 2 h at 500 °C. These micrographs show obvious carbides in Fig. 5(b), and coarse grain boundary precipitation in the C-free sample and relatively fine precipitation throughout the C-containing sample. Electron diffraction patterns show no maxima due to ω.

Figure 6 shows examples of the microstructures observed after aging quenched samples for 2 h at 600 °C. The C-free sample (Fig. 6a) again shows a coarse grain boundary and matrix α precipitates, but the precipitates in the C-containing sample (Fig. 6b) are not resolved.

The fracture surfaces of samples in Fig. 7 show that the poor ductility in the C-free sample is associated with grain boundary failure in this very coarse grained sample. Although the ductility of the as-quenched sample of Ti-13Cr is also very low, the failure is found to be transgranular and is associated with the ω phase that is present in the as-quenched samples, as noted earlier. The α precipitation during aging has clearly led to the tendency to grain boundary failure.

In view of the dual role of carbides (refining the grain size and reducing the local oxygen content in the grain boundaries) in influencing the extent of grain boundary precipitation, the

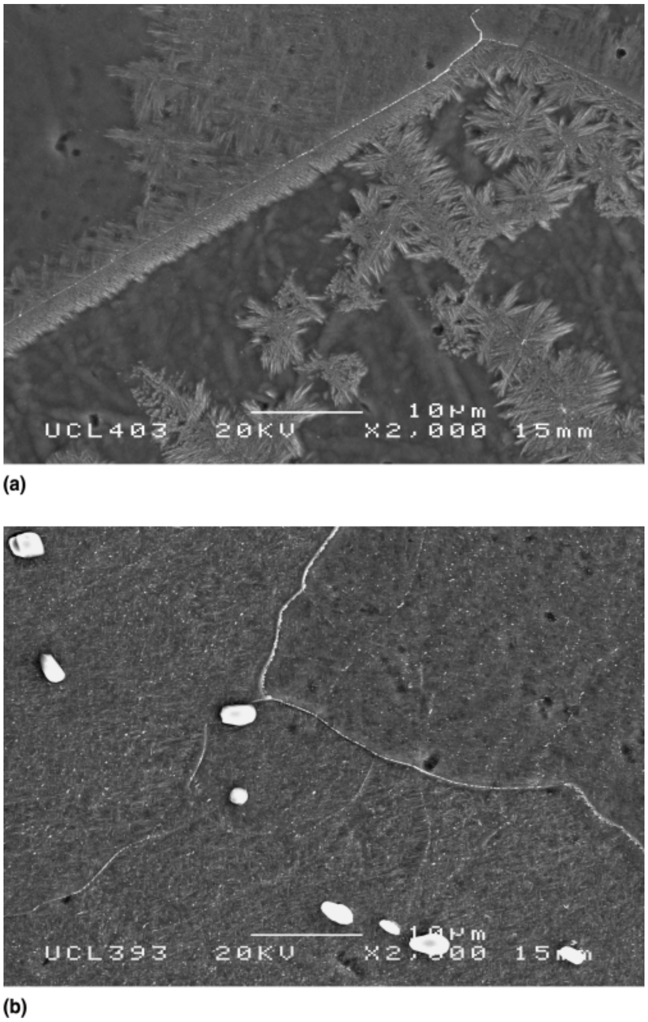

Fig. 5 Secondary electron micrographs of Ti-13Cr quenched from 950 °C and aged for 2 h at 500 °C: (a) C-free; (b) C-containing sample

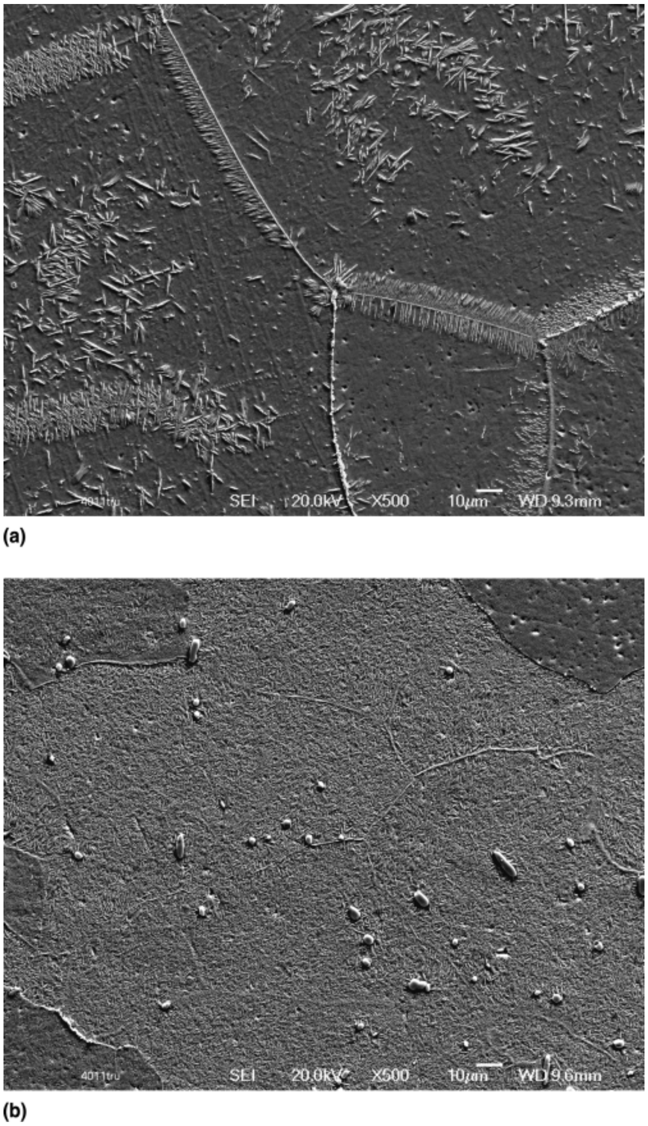

Fig. 6 Secondary electron micrographs of Ti-13Cr quenched from 950 °C and aged for 2 h at 600 °C: (a) C-free; (b) C-containing sample

same volume fraction of ytrria has been introduced, with the aim of pinning the grain boundaries, but without changing the local oxygen content. The result of quenching and aging such a sample for 0.5 h at 600 °C is shown in Fig. 8, where the extent of grain boundary α is compared in the C-free alloy, the C-containing alloy, and the yttria-containing alloy. It is clear that the grain boundary α precipitation is reduced by the presence of yttria but not to the same extent as that by the presence of the titanium carbide. It thus follows that the reduction in grain size, which leads to an increase in grain boundary area and thus to a decrease in grain boundary oxygen content, leads to a reduction in the grain boundary precipitation of α. The larger effect of carbon shows that the reduction of the local oxygen concentration through the formation of Ti(C_xO_y) is also significant. The matrix α follows the same trend with coarse α in the C-free, very fine α in the C-containing sample, and with α grains of intermediate size in the yttria-containing sample.

The extent of the removal of oxygen from the matrix has been assessed using wavelength dispersive x-ray (WDX) analysis by taking x-ray data using identical conditions of the beam current and other variables for the same fixed times on the carbides and on the matrix. The results are shown in Table 2, which shows the total count obtained in the oxygen window for the carbide and matrix. It is apparent that the carbides contain some oxygen, but only at about the same level (900 ppm) as is present in the matrix. The difference between these total counts is not significant, because for such a small number of counts the error is about 20%. It is thus clear that the Ti carbides are not as effective at reducing the oxygen content as has been found in Ti-25V-15Cr-2Al (Ref 1).

4. General Discussion and Summary

The observations made on Ti-13Cr with and without the addition of C show that the changes in aging characteristics are qualitatively in line with those found in other alloy systems where Ti_2C rather than TiC is formed. The most important role of carbon addition is the virtual total elimination of grain boundary α during aging. As is obvious from the results shown here, grain boundary α results in a severe reduction in ductility, and its elimination through a combination of grain refinement and oxygen removal by the carbides is very significant. However, the impact of C on the aging response is not as great as that in the case of Ti-15-3 (Ref 9). The reduced influence on

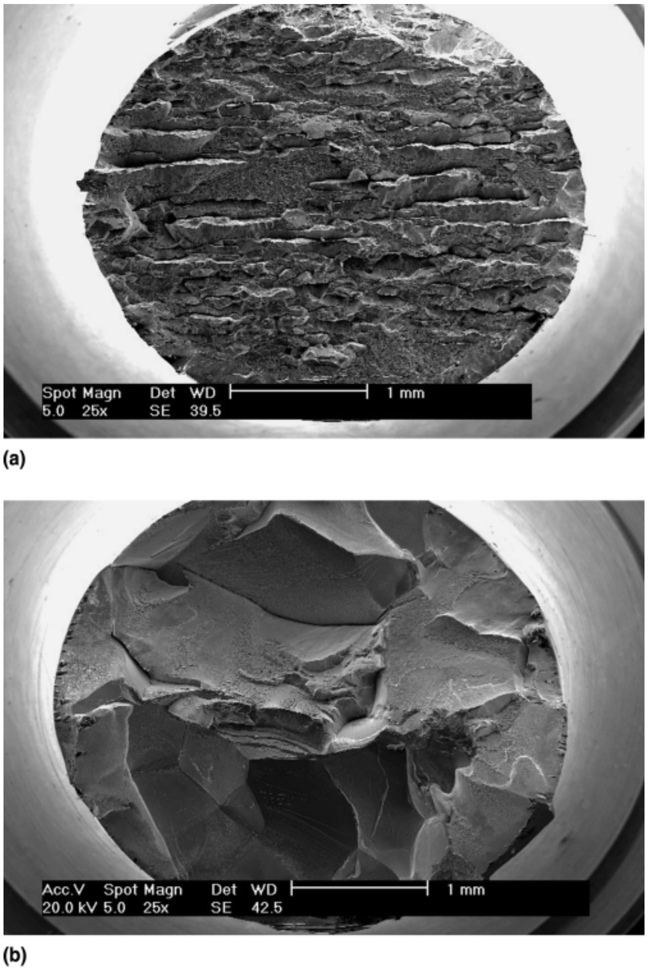

Fig. 7 Secondary SEM images showing the fracture surfaces of (a) C-free Ti-13Cr and (b) Ti-13Cr-0.15C after quenching from 950 °C and aging for 2 h at 500 °C

Table 2 Number of oxygen x-ray counts obtained under identical electron optical conditions from the matrix and from the carbides in a sample of Ti-13Cr-0.15C

Condition	O counts, No.
Matrix	109
Carbide	97

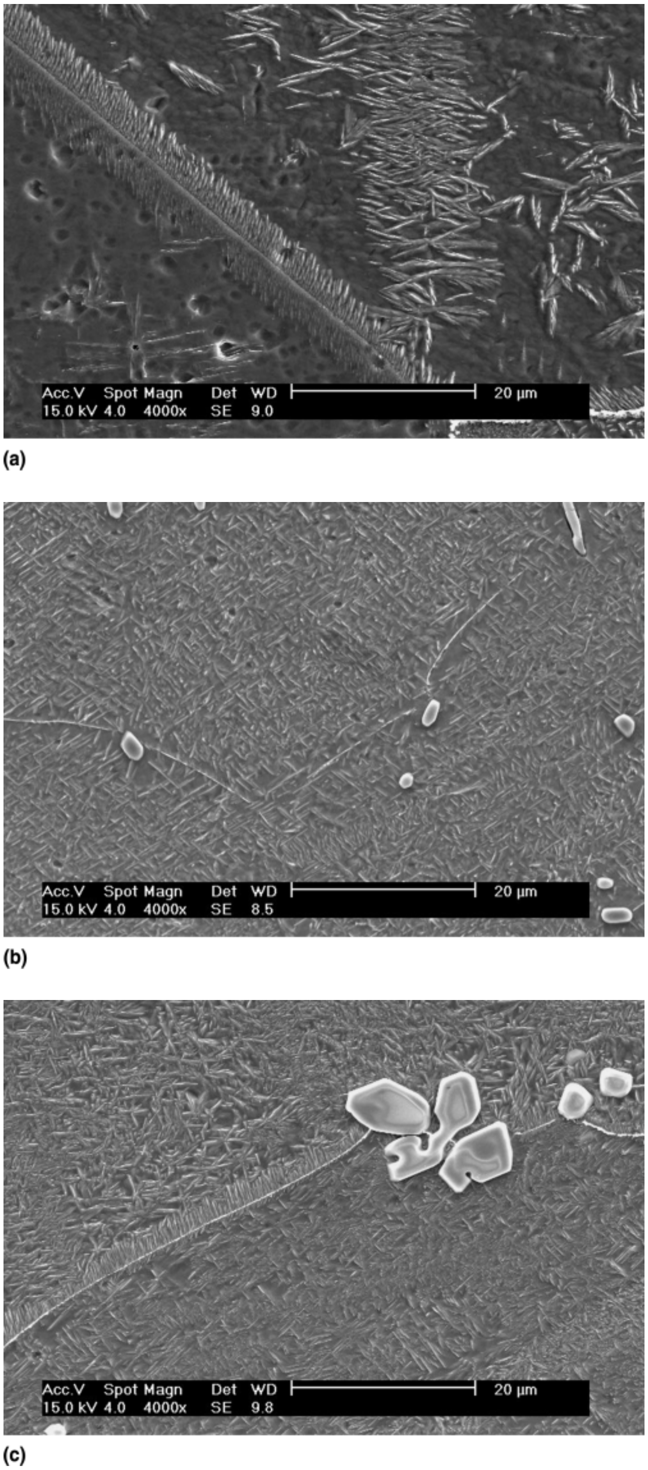

Fig. 8 Grain boundary precipitation of α after aging for 0.5 h at 600 °C for (a) Ti-13Cr, (b) Ti-13Cr containing Ti_2C, and (c) Ti-13Cr containing Y_2O_3

hardening response seen in Ti-13Cr compared with that in Ti-15-3 is likely to be associated with the fact that athermal ω is formed in Ti-13Cr but not in Ti-15-3, and this ω will influence α precipitation in the early stages of aging. The drop in hardness observed in the early stages of aging at the lower temperatures is presumably associated with a reduction in ω before α precipitation dominates. The relatively low concentration of oxygen found in the carbides here is consistent with the limited improvement in ductility observed in Ti-13Cr when compared with that found in Ti-25V-15Cr-2Al (Ref 1). The addition of C, of course, not only influences the oxygen content of the matrix but it also affects the extent of ω formation, and generates dislocations and elastic stresses that are associated with quenching strains. It is thus not easy to interpret the role that C plays on the age-hardening response. The observation that yttria addition refines the grain boundary and the matrix precipitation of α indicates that dislocations and/or elastic stresses are both important. Clearly, further detailed TEM is required before the results can be fully understood.

Acknowledgments

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