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To cite this article: M S Ozerov *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1014** 012039

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Effect of carbon on microstructure and mechanical properties of titanium

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Abstract. The microstructure and mechanical properties of cold rolled titanium with 0.0, 0.1 and 0.2 wt.% of carbon were studied after annealing in a temperature range of 500-800 °C. The addition of carbon resulted in slower grain growth kinetics and less intensive softening during annealing of the cold rolled alloys in the temperature range 500-800 °C. Besides, the alloys with carbon are considerably stronger in comparison with pure titanium; cold rolling resulted in an increase in the yield stress from 540 MPa for titanium to 630 and 605 MPa for Ti-0.1C and Ti-0.2C, respectively. However, ductility of the carbon doped titanium was also found to be decreased to ~32% in comparison with 40% for pure titanium.

1. Introduction

Titanium alloys are extremely important structural materials widely used in chemistry, medicine, automobile, shipbuilding and aerospace industry [1, 2]. Titanium based alloys are primarily used in structures that require a combination of high specific strength and corrosion resistance. Alloying of titanium is an effective method for controlling their structure and properties [3-5]. It was found that carbon can increase strength of titanium significantly; however the most effective is solid solution strengthening, while precipitation (carbide) strengthening does not contribute into strength notably [6-9]. Besides, the carbides formation can result in a drop in ductility. Another possible effect of carbon can be associated with the preferential distribution of carbon at grain boundaries thereby decreasing their mobility. This can be used for increasing the stability of a fine-grained structure at elevated temperatures.

In the present work, titanium with 0.0, 0.1 and 0.2 wt.% of carbon was cold rolled and then annealing at temperatures 500-800 °C for one hour. Structure, microhardness and grain growth kinetics were examined as a function of the annealing temperature.

2. Materials and methods

Pure titanium (99.1% purity) and titanium 0.1 and 0.2 wt.% of carbon (Ti-0.1C and Ti-0.2C, respectively) were studied. Since the maximum solubility of carbon in titanium at room temperature is ~0.2 wt.%, this amount of carbon should form solid solution in both cases. The alloys were obtained by vacuum arc melting. Flat samples were rolled at room temperature to a total strain of 1.2 (70% thickness reduction). Then they were annealed at 500, 600, 700 and 800 °C for 60 min.



Samples for metallographic studies was prepared by mechanical grinding with finish polishing using a colloidal suspension of silicon dioxide (SiO_2 , the crystallite size of about $0.04 \mu\text{m}$). For chemical etching, a mixture of 0.25 ml of HF, 1.75 ml of HCl and 53 ml of water was used. Microstructural studies were carried out using a Quanta 600 field emission gun (FEG) scanning electron microscope (SEM) and a Nova NanoSEM 450 SEM.

Vickers microhardness was measured at room temperature using 200g load for 10s; 10 measurements were made for each specimen.

3. Results and discussion

3.1. Initial microstructure

The as-cast microstructure in all program materials was rather coarse with an average grain size of $\sim 1 \text{ mm}$ (Figure 1a-c). XRD showed that pure titanium and Ti-0.1C, Ti-0.2C (Figure 1d) consisted of hcp α -Ti solely without carbide phases.

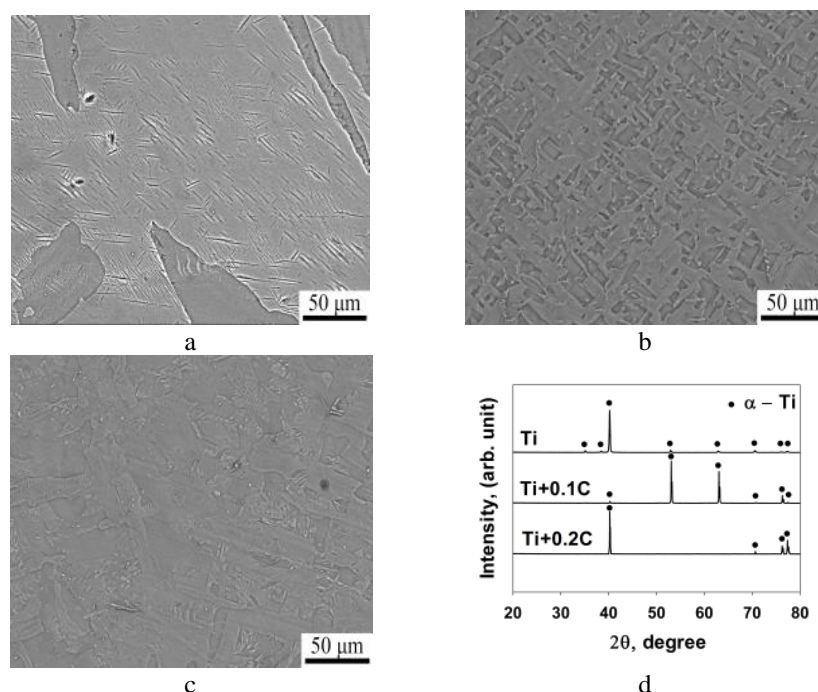


Figure 1. Microstructure images (a – c) and XRD pattern (d) of Ti (a), Ti-0.1C (b) and Ti-0.2C (c) in the initial condition.

3.2. Microstructure evolution after rolling and during subsequent annealing

Annealing of the cold rolled titanium alloys at $500\text{--}800 \text{ }^\circ\text{C}$ resulted in the formation of an equiaxed structure in all studied alloys (Figure 2). However, the addition of carbon to titanium led to a decrease in the kinetics of grain growth during annealing at 700 and $800 \text{ }^\circ\text{C}$ (Figure 3). The smallest grain size was detected at the carbon content of 0.1 percent. It was found that after rolling at room temperature and annealing, the grain size of the alloy with 0.1wt.% of C was ~ 40 percent smaller than that in pure titanium: $45\mu\text{m}$ vs. $73 \mu\text{m}$ at $800 \text{ }^\circ\text{C}$ and $5\mu\text{m}$ vs. $3 \mu\text{m}$ at $500 \text{ }^\circ\text{C}$. Similar result after addition of 0.05 and 0.15% C was earlier reported in [7, 8]. It should be noted that grains in the Ti-0.2C alloy was slightly larger than those in Ti-0.1C. However, this difference was within the measurement error. Thus, alloying of pure titanium with carbon results to inhibition of the grain growth kinetics after cold rolling and annealing in the temperature range $500\text{--}800 \text{ }^\circ\text{C}$.

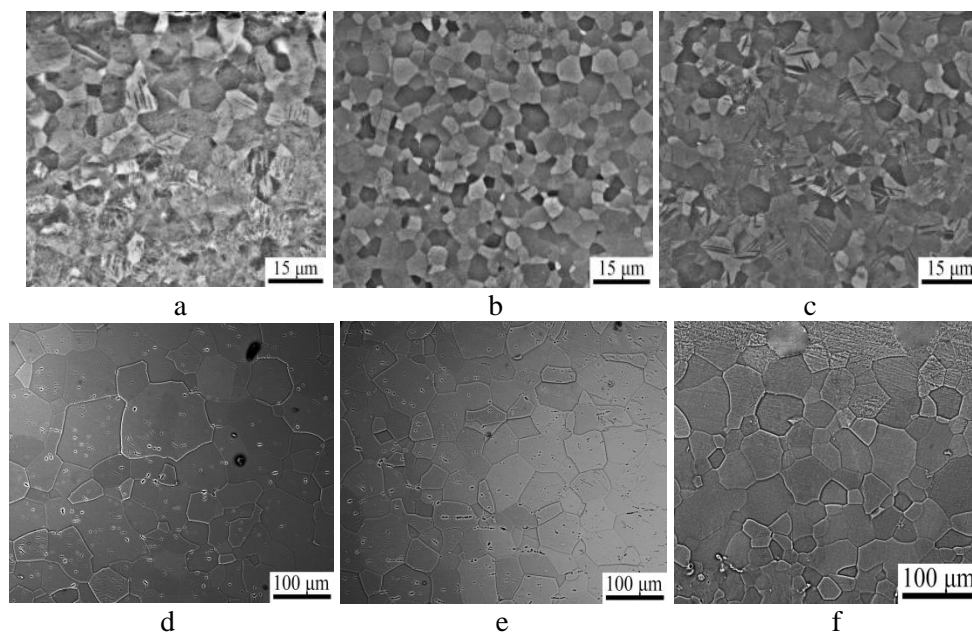


Figure 2. Microstructure images of cold rolled Ti (a, d), Ti-0.1C (b, e) and Ti-0.2C (c, f) after annealing at 500 °C (a – c) and 800 °C (d – f).

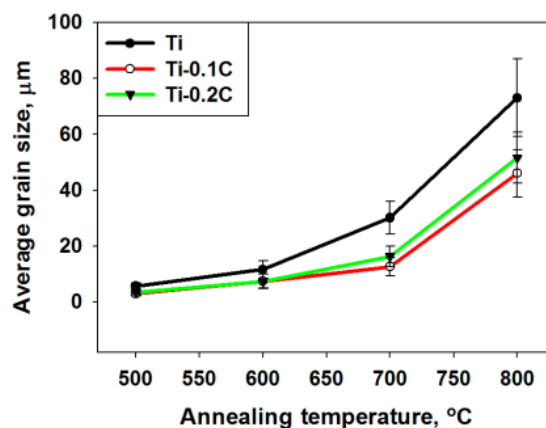


Figure 3. Effect of annealing temperature on the average grain size of cold rolled titanium and Ti-0.1C, Ti-0.2C alloys.

3.3. Mechanical properties of the alloys after cold rolling and subsequent annealing

In the as-cast condition the yield stress of the alloys with carbon was ~55% higher in comparison with that of pure titanium (~300 MPa vs. 170 MPa) (Figure 4a). The yield stress values for the Ti-0.1C and Ti-0.2C alloys were almost identical. Rolling at room temperature led to an increase in the yield stress to 540 MPa for titanium and to 630 and 600 MPa for the Ti-0.1C and Ti-0.2C alloys, respectively (Figure 4a). Tensile elongation for titanium in the as-cast was 48%. Ductility of the alloys with 0.1wt.% and 0.2wt.% of carbon was slightly lower: 38% and 40%, respectively (Figure 4b). Cold rolling led to a considerable decrease in the ductility values by 32-40% in all studied alloys.

Microhardness analysis also shows a considerable hardening of all alloys after cold rolling (Figure 4c). The microhardness value of pure titanium increased from 117 HV in the as-cast state to 240 HV after cold rolling. The alloys with 0.1 and 0.2% of C had in the initial state microhardness of 157 and 153 HV, respectively. Cold rolling increased these values to 257 and 252 HV, respectively. The obtained results confirm the strengthening effect of carbon without significant change in ductility [7-9].

Annealing in the temperature range 500-800 °C led to a decrease in the microhardness for all states, however, the decrease in the microhardness of pure titanium was more intensive (microhardness dropped from 240 to 118-89 HV) compared to Ti-0.1C and Ti-0.2C alloys (microhardness values from 257 HV and 252 HV in the initial state decreased to 184-171 HV and 178-166 HV after annealing, respectively).

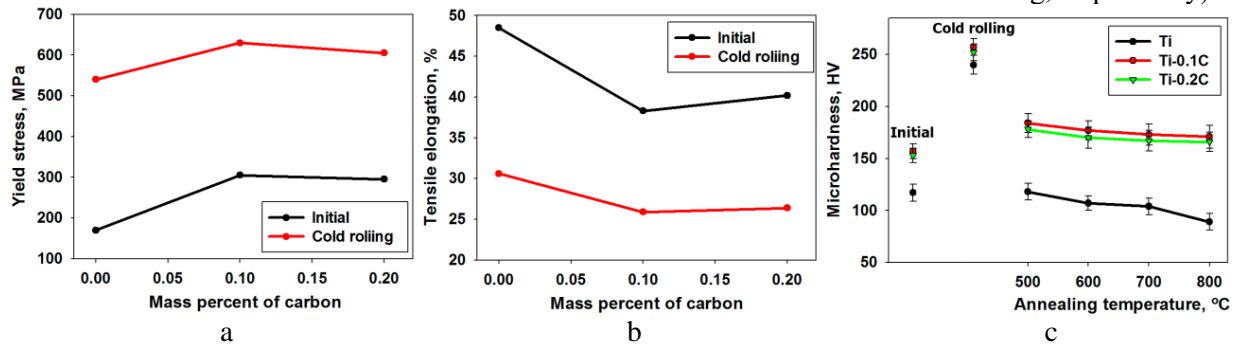


Figure 4. Effect of carbon content (a, b) and annealing temperature (c) after rolling and subsequent annealing on mechanical properties of titanium and Ti-0.1C, Ti-0.2C alloys.

4. Conclusions

Based on the results of the study, the following conclusions were drawn:

- i) Alloying of pure titanium with carbon led to inhibition of the kinetics of grain growth during annealing at 500-800 °C of the cold rolled alloys;
- ii) The yield stress of alloys with carbon was ~55 percent higher in comparison with pure titanium (~300 MPa vs. 170 MPa); cold rolling led to an increase in the yield stress to 540 MPa of titanium and to 630 and 605 MPa of Ti-0.1C and Ti-0.2C alloys, respectively;
- iii) Annealing in the temperature range 500-800 °C resulted in a decrease in the microhardness of all the alloys, however, the decrease in the microhardness of pure titanium was more intensive in comparison with Ti-0.1C and Ti-0.2C.

Acknowledgment

The work was supported by the Russian Science Foundation under Grant № 19-79-30066. The authors are also grateful to Joint Research Center “Materials and Technologies”, Belgorod State University, for the assistance with instrumental analysis.

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