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Effect of solutes on the rate sensitivity in Ti-xAl-yMo-zV and Ti-xAl-yMo-zCr β-Ti alloys

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ABSTRACT

The strain rate sensitivity (m) of Ti-xAl-yMo-zV and Ti-xAl-yMo-zCr bcc-Ti alloys has been investigated as a function of composition by a high throughput approach based on diffusion multiples and mechanical property screening by micropillar compression. It is shown that the influence of a solute species depends on the alloy composition. In particular, increasing levels of Mo result in a decrease of m in Ti-xAl-yMo-zV alloys, while they do not have a significant effect in the Ti-xAl-yMo-zCr system. The measured m values are related to the active deformation systems and to the flow stress and activation volume of the investigated alloys.

The strain rate sensitivity (m) of a metallic material gives a measure of the dependence of its flow stress (σ) on external testing conditions such as the temperature (T) or the applied strain rate ($\dot{\varepsilon}$) [1]. Its value may vary between 0 and 1 (Newtonian fluid). When a material's response is strain rate sensitive, a considerable delay in necking may occur [2]. Superplastic materials, with m values higher than 0.3, are able to withstand elongations of several hundred percent before failure and, thus, constitute a very evident case of the influence of m on ductility [3]. The strain rate sensitivity can be written as [4]:

$$\mathrm{m} = \frac{\partial(log\sigma)}{\partial(\ log\dot{\varepsilon})} \tag{1}$$

or, in terms of the activation volume (ν^*), as [5]:

$$\mathrm{m} = \sqrt{3}kT/\sigma\nu^* \tag{2}$$

The plasticity of body centered cubic (bcc) metals has been less studied than that of face centered cubic (fcc) metals and research efforts on this area remain mostly confined to pure metals. The influence of alloying remains rather unexplored in spite of some recent remarkable efforts in this direction [6,7]. Single crystals and coarse grained polycrystals of pure metals with bcc structures have, in general, higher strain rate sensitivity than those with fcc lattices [4]. This is due to the fact that plasticity in bcc metals, at least in the early stages of deformation, is governed by slip of screw dislocations, which dissociate onto three different planes [8], rendering a very complex dislocation core with very limited mobility. The movement of such screw dislocations is believed to be controlled by the nucleation of double kinks, a thermally activated process [9–12]. In fcc metals, on the contrary, dislocations may dissociate into two partials on one slip plane, and they can glide easily, with little need for thermal assistance. A reduction in grain size from the microcrystalline to the nanocrystalline range gives rise to a decrease in the m value in bcc metals [5]. Different explanations have been put forward to rationalize this observation. Earlier works [13] have assumed that the double kink nucleation mechanism would still be rate controlling in nanocrystalline bcc metals, rendering ν^* constant for sufficiently high stress levels, and attributed the lower m values observed to the increase in strength due to the Hall-Petch effect (Eq. (2)). More recently, Cheng et al. [14] have reported a gradual replacement of screw dislocations by edge and mixed dislocations with decreasing grain size in pure Mo; the strain rate sensitivity decrease would then be related to the easiness of glide of the latter. The effect of solute additions on the strain rate sensitivity of bcc metals remains still a rather unexplored subject.

β-Ti alloys constitute excellent systems to investigate the effect of multicomponent alloying additions on m in bcc metals. These materials, with a bcc lattice structure, and which contain large amounts of alloying additions, are a very versatile class of materials, which may achieve very high strength after proper heat treatments due to both solute and

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precipitation strengthening effects [15]. Comprehensive data about the high temperature rate sensitivity of β-Ti alloys has been published [16,17]. However, relatively little work has been carried out to date to understand the effect of alloying additions on the room temperature strain rate sensitivity of these materials. Recent research [18], combining pillar compression and crystal plasticity modelling, determined indirectly the strain rate sensitivity of the bcc Ti phase in a Ti-6Al-2Sn-4Zr-2Mo (wt%) alloy, finding it to be much higher than that of the corresponding α Ti phase. Understanding the strain rate sensitivity of β-Ti alloys is reportedly critical to optimize cold dwell fatigue behavior [19].

The aim of this work is to utilize the high throughput technique of diffusion multiples to investigate the effect of solute additions on the room temperature strain rate sensitivity of quaternary β-Ti alloys. The obtained m values have been related to the active deformation mechanisms and the nature of the dislocations present.

A diffusion multiple composed of pure Ti and three Ti ternary alloy blocks (Ti-7.7Al-8.4V, Ti-13.4Al-12.4Mo, Ti-7.7Al-8.1Cr, wt%) was arranged as shown in Fig. 1. The different steps of the processing have been described in detail in [20]. The multiple was annealed at high temperature for several hours in order to facilitate uniaxial diffusion in a direction perpendicular to the interfaces. The two interdiffusion regions of interest for the current study are those developed between Ti-7.7Al-8.4V and Ti-13.4Al-12.4Mo (wt%), hereafter referred to as β_1, and between Ti-13.4Al-12.4Mo and Ti-7.7Al-8.1Cr (wt%), hereafter referred to as β_2. Both interdiffusion regions are single crystalline and their widths are approximately 500 μm; the surface normal directions were identified as [113] and [134], respectively, via electron backscatter diffraction (EBSD) analysis. The composition gradient developed across these two interdiffusion regions, measured by electron probe microanalysis (EPMA) using a JEOL Superprobe JXA 8900 microscope with a voltage of 20 kV and a current of 50 nA, is also plotted in Fig. 1.

Several alloy compositions were selected, respectively, within β_1 and β_2, in order to evaluate solute effects on the rate sensitivity. These compositions (a total of 3 in β_1 and 4 in β_2), are summarized in Table 1 and are labeled C_i in Fig.1. Within β_1, the Mo content increases between 6 and 12 wt%, while the variations of Al and V remain within 1 wt%; within β_2, Al remains also relatively unchanged, while the content of Mo and Cr changes noticeably ($\Delta_{Mo} \approx 9$ wt% and $\Delta_{Cr} \approx 5$ wt%).

Table 1
Selected alloy compositions selected within the two interdiffusion regions under study.

		V (wt%)	Mo (wt%)	Al (wt%)	Ti (wt%)
β_1	C1	2.935 ± 0.021	5.701 ± 0.077	9.856 ± 0.046	Bal.
	C2	2.306 ± 0.032	9.571 ± 0.124	10.474 ± 0.058	Bal.
	C3	1.846 ± 0.16	11.737 ± 0.093	11.345 ± 0.042	Bal.
		Cr (wt%)	Mo (wt%)	Al (wt%)	Ti (wt%)
β_2	C1	6.389 ± 0.003	1.185 ± 0.001	9.223 ± 0.017	Bal.
	C2	5.280 ± 0.001	2.946 ± 0.001	9.630 ± 0.011	Bal.
	C3	4.292 ± 0.001	5.718 ± 0.007	9.791 ± 0.001	Bal.
	C4	2.187 ± 0.000	9.912 ± 0.001	10.528 ± 0.003	Bal.

Square micropillars were milled at the selected alloy compositions within β_1 and β_2 using a focused Ga + ion beam (FIB), with an accelerating voltage of 30 kV, in a FEI Helios NanoLab 600i dual-beam field emission gun scanning electron microscope (FEGSEM). All the pillars were machined following an efficient annular milling strategy. A range of ion beam currents were employed at different milling stages; a current of 80 pA was used for the final milling step in order to minimize surface damage due to Ga^+ ion-implantation. A micropillar side length of 5 μm and an aspect ratio of ~2.4 were chosen, as earlier studies have demonstrated that this geometry yields mechanical properties that are free of size effects [20]. Fig. 1 also illustrates the micropillar array within interdiffusion region β_1.

Two types of tests were performed in order to investigate the effects of composition on the rate sensitivity. On the one hand, strain rate jump micropillar compression tests (SRJMC) were used to measure the strain rate sensitivity in all the β-Ti alloy compositions investigated. The strain rate was changed between the values $10^{-4}\,s^{-1}$, $7 \times 10^{-4}\,s^{-1}$, $5 \times 10^{-3}\,s^{-1}$, and $10^{-2}\,s^{-1}$ and the corresponding flow stresses were recorded. The strain rate sensitivity (m) was then calculated as the slope of the log (stress)-log (strain rate) plot. Each test was repeated at least 3 times. To reduce the influence of thermal drift between the flat punch indenter and the micropillars, all compression tests were performed after a long contact period of up to 600 s. In order to minimize the stress drops originated by dislocation avalanches, which could lead to a misinterpretation of the stress data, micropillars were milled with a taper

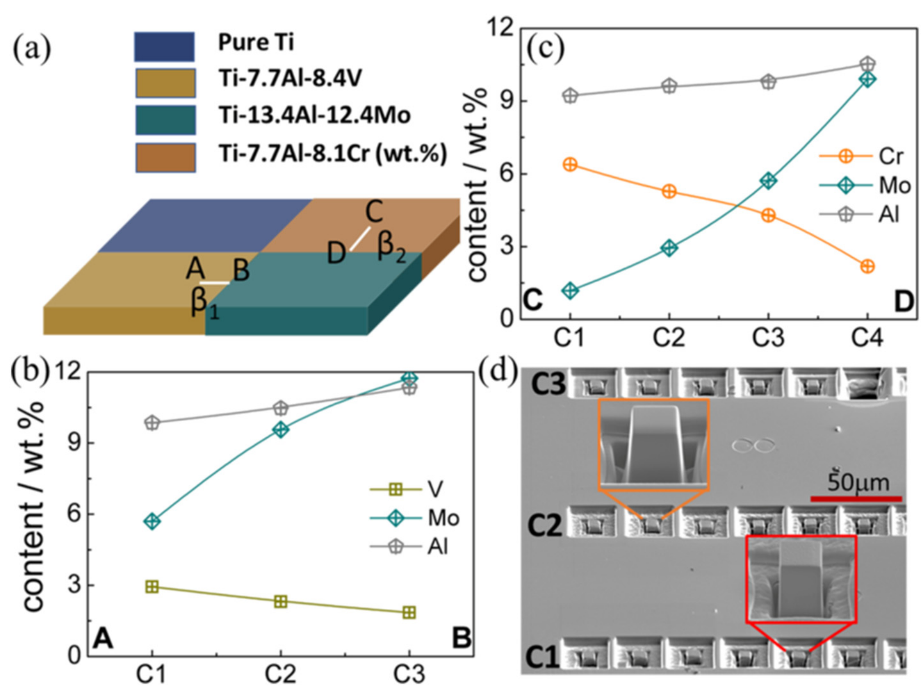

Fig. 1. (a) Schematic drawing of diffusion multiple where the selected β_1 and β_2 interdiffusion regions are indicated; (b), (c) composition of the selected alloys within interdiffusion regions β_1 and β_2; (d) SEM micrograph illustrating the micropillars milled within region β_1.