Effect of microstructure on tensile properties and fracture behavior of intermetallic Ti$_2$AlNb alloys[①]

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[Abstract] The tensile properties and fracture behaviors of Ti-22Al-27Nb and Ti-22Al-20Nb-7Ta alloys were investigated in the temperature range of 25~ 800 ℃. Three typical microstructures were obtained by different thermomechanical processing techniques. The results indicate that the duplex microstructure has an optimum combination of tensile yield strength and ductility both at room and elevated temperatures. Adding Ta to Ti$_2$AlNb alloy can improve the yield strength, especially at high temperature while retain a good ductility. The study on crack initiation and propagation in deformed microstructure of Ti$_2$AlNb alloys indicates that microstructure has important effect on the tensile fracture mechanism of the alloys. The cracks initiate within primary O/α_2 grains along $O/B2$ boundaries or O phase laths in $B2$ matrix, and propagate along primary $B2$ grain boundaries for the duplex microstructure. The fracture mode is transgranular with ductile dimples for the duplex and the equiaxed microstructures, but intergranular for the lath microstructure.

[Key words] Ti$_2$AlNb based alloy; microstructure; property; fracture

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1　INTRODUCTION

Ti$_2$AlNb orthorhombic alloys exhibit potential as high temperature structure materials for aerospace application because of their high specific strength and fracture toughness as well as good creep resistance[1, 2]. Recently numerous studies have been focused on the relationship among processing, microstructure and mechanical properties of Ti$_2$AlNb orthorhombic alloys[3~ 10]. It is found that the mechanical properties of Ti$_2$AlNb based alloys depend on microstructures. The effect of thermo-mechanical processing on microstructure of the alloys is similar to that of conventional ($\alpha+ \beta$) titanium alloys. Alloying and thermo-mechanical processing are the most effective approaches to improve the comprehensive properties of orthorhombic alloys. The deformation under transus temperature could refine the microstructure and optimize the mechanical properties, and the replacement of a part of Nb with Mo, W and V has been studied to improve the yield strength and creep resistance at improve the yield strength and creep resistance at high temperatures. Especially the replacement of Nb with Ta has significant effect on improving strength and ductility at both room and high temperatures (650 ℃). The yield strength and elongation at 650 ℃ reach 985 MPa and 13%, respectively[8]. The purpose of this study is to examine the tensile properties in temperature range of 25~ 800 ℃ of Ti-22Al-27Nb and Ti-22Al-20Nb-7Ta alloys with three type microstructures, to investigate their fracture behaviors including the fracture mode and fracture process consisting of microcracks initiation and propagation, and to analyze the strengthening effect of Ta in more detail.

2　EXPERIMENTAL

Cast ingots with the nominal composition of Ti-22Al-27Nb and Ti-22Al-20Nb-7Ta were prepared by induction skul melting (ISM), and remelted 3 or 4 times to ensure the composition homogenization. The chemical analysis showed that the composition of the cast ingots was in agreement with nominal composition, and the interstitial contents were lower (e. g., $w(O) \leqslant 5 \times 10^{-4}$, $w(H) \leqslant 3 \times 10^{-5}$, $w(N) \leqslant 8 \times 10^{-5}$). The cast ingots canned with stainless steel were forged to a rod with a diameter of 25 mm at 1 100~ 1 150 ℃ in $B2$ phase field after homogenizing at 1 180 ℃ for 24 h. Then the rod was rolled to 4 mm thick sheet by multiple passes in ($\alpha_2+ B2+ O$) or ($O+ B2$) phase fields. Samples used for microstructure observation were cut from these sheets. Three type microstructures were obtained by different thermo-mechanical processing (TMP). Lath microstructure was obtained by TMP1 treatment consisting of solution above $B2$ transus temperature followed by annealing at ($O + B2$) phase field. Equiaxed microstructure was obtained by TMP2 treatment consisting of rolling and solution at ($O + B2$) phase field. Duplex microstructure (DP) was obtained by

TMP3 treatment consisting of rolling at (α_2+ $B2$+ O) phase field and solution plus aging at (O+ $B2$) phase field.

The tensile and in-situ tensile specimens with effective gauge length of 22 mm were prepared by electron-discharged from the heat-treated rolled sheets. Selected in-situ tensile specimens were finely polished to satisfy the requirement for metallography examination prior to tesing. Tensile tests were performed on MTS-810 machine from room temperature to 800 ℃ in air. In-situ tensile tests were performed on JSM-5800 scanning electron microscope (SEM) by the tensile equipment to investigate the crack initiation and propagation during fracture processing. The microstructure and the phases of the alloys through different TMP treatments were observed and analyzed with SEM, TEM and XRD. The phase volume fractions were determined quantitatively using SEM image analysis software on a JSM-6400 SEM. The fractographic features of the tensile samples were evaluated by SEM.

3 RESULTS

3. 1 Microstructure

Fig. 1 shows the SEM second electron images of three type microstructures: lath, equiaxed and duplex microstructures for Ti-22Al-20Nb-7Ta alloys after the different TMP treatment. According to Nb content in constituent phases, the dark contrast is α_2 phase, the bright contrast is $B2$ phase and the gray contrast is O phase. Fig. 1(a) shows the lath microstructure with TMP1 treatment. The supper-transus solution led to the large primary $B2$ grain boundaries remained. The dominant microstructure was laths of (O+ $B2$) phases formed during aging in (O+ $B2$) phase field. Fig. 1(b) shows the equiaxed microstructure obtained through TMP2 treatment, showing fine equiaxed O phase grains distributed in $B2$ matrix. The volume fraction of O phase, $\varphi(O)$, was dependent on the solution temperature, that is, the $\varphi(O)$ increases with decreasing the temperature. $\varphi(O)$ is about 30% for the sample solution treated at 950 ℃. Fig. 1 (c) shows the duplex microstructure (DP) obtained with TMP3 treatment. The duplex microstructure consists of the fine α_2/O particles and extremely fine and crisscross lath-like O phase (1~ 2 μm) distributed in the $B2$ matrix without primary $B2$ phase grain boundaries remained. The total volume fraction of O phase is up to about 75% in this microstructure.

3. 2 Tensile properties

Fig. 2 shows the tensile properties of three type microstructures of Ti-22Al-20Nb-7Ta alloy at room temperature. The results showed that mechanical properties of the alloy are strongly dependent on the microstructures. The lath microstructure remaining
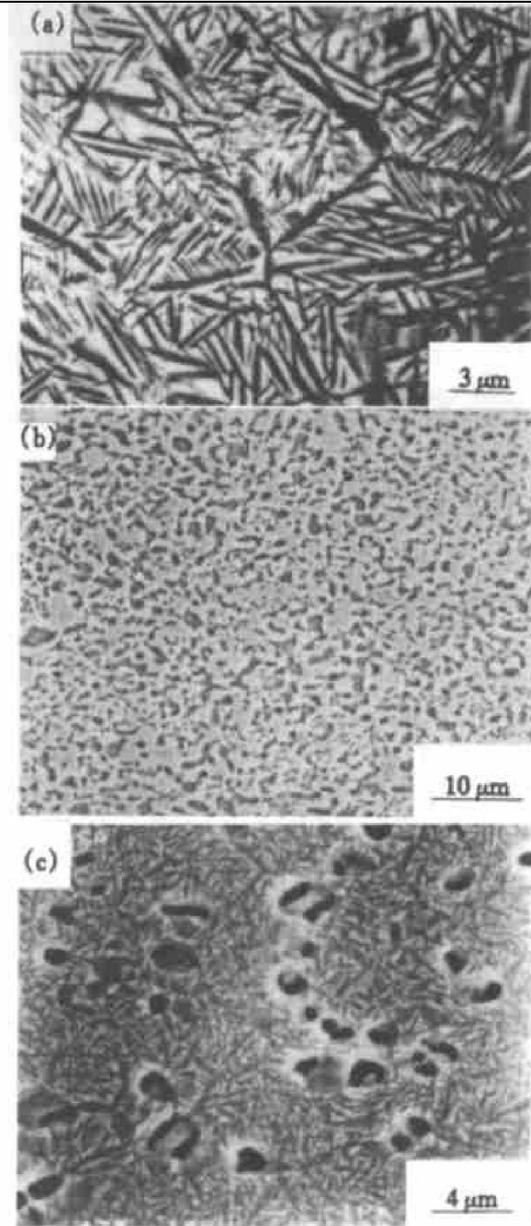

Fig. 1 SEM micrographs of Ti-22Al-20Nb-7Ta alloys with various TMP treatments
(a) —Lath microstructure(TMP1 treatment);
(b) —Equiaxed microstructure(TMP2 treatment);
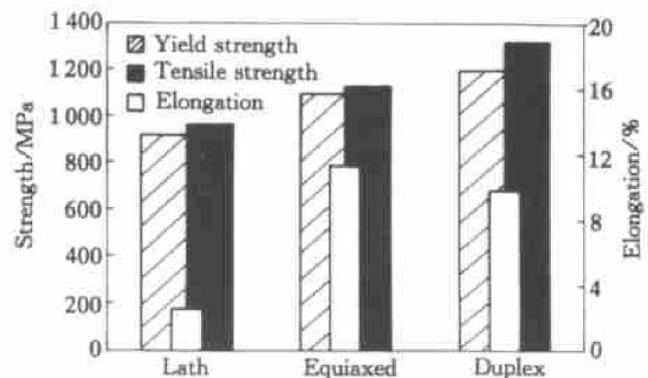(c) —Duplex microstructure(TMP3 treatment)

Fig. 2 Tensile properties of three type microstructures of Ti-22Al-20Nb-7Ta alloy

coarse primary $B2$ grain boundaries possesses lower strength and ductility such as $\sigma_{0.2}$= 920 MPa, δ= 1.8%. The equiaxed microstructure possesses the

highest ductility and higher strength, for example $\sigma_{0.2} = 1\ 100$ MPa, $\delta = 11.3\%$. The duplex microstructure without remaining coarse $B2$ grain boundaries has the best combination of strength and ductility, and the yield strength and ductility are up to 1 200 MPa and 9.8%, respectively.

　　Table 1 lists the tensile properties of the duplex microstructure from room temperature to 800 ℃ for Ti-22Al-27Nb and Ti-22Al-20Nb-7Ta alloys. Comparing Ti-22Al-20Nb-7Ta alloy with Ti-22Al-27Nb alloy, the former possesses higher yield strength at both room and elevated temperatures, while has almost the same ductility as the latter.

Table 1　Comparison of tensile properties of Ti-22Al-27Nb and Ti-22Al-20Nb-7Ta alloys with duplex microstructure (TMP3 treatment) at room and elevated temperatures

Temperature/ ℃	Ti-22Al-27Nb			Ti-22Al-20Nb-7Ta		
	$\sigma_{0.2}$/ MPa	σ_b/ MPa	δ_5/ %	$\sigma_{0.2}$/ MPa	σ_b/ MPa	δ_5/ %
RT	1 050	1 160	10.1	1 200	1 320	9.8
300	975	1 120	13	1 100	1 260	10
400				1 045	1 240	9.5
500	915	1 020	16	1 000	1 175	12
650	820	875	14	985	1 080	13
750	687	837	13	840	970	8.5
800				745	800	12

RT —Room temperature

　　Fig. 3 shows the dependence of strength and ductility on temperature for Ti-22Al-27Nb and Ti-22Al-20Nb-7Ta alloys with duplex microstructure. The strengths of the two orthorhombic alloys all decrease with temperature, but the addition of Ta to substitute part of Nb can improve the yield strength, especially the high temperature yield strength, while retain a good ductility. The yield strength of Ti-22Al-27Nb dropped rapidly above 500 ℃, while that of Ti-22Al-20Nb-7Ta decreased obviously over than 650 ℃. The yield strength of Ti-22Al-20Nb-7Ta alloy was 985 MPa at 650 ℃, and 840 MPa even at 750 ℃. The ductility is characterized by a significant increase of the total elongation with increasing temperature and a minimum value around 700 ℃.

3.3　Fracture behavior

　　Fig. 4 shows the crack initiation and propagation of in-situ tensile processing of Ti-22Al-20Nb-7Ta alloy with equiaxed and duplex structures. The microcracks initiated and propagated at or along slip-bands for equiaxed microstructure(as shown in Fig. 4(a) and Fig. 4(b)). For the duplex microstructure the microcracks initiated in α_2/O grains and O phases
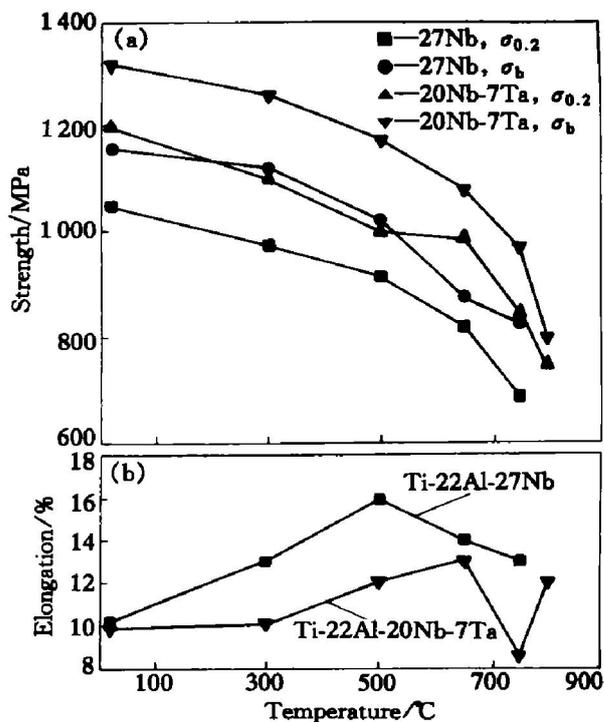

Fig. 3　Tensile properties as a function of temperatures for Ti-22Al-27Nb and Ti-22Al-20Nb-7Ta alloys

laths in $B2$ matrix or along the $O/B2$ interface (as shown in Fig. 4(c)), and propagated along O phases laths in $B2$ matrix and linked by ductile tearing of the $B2$ phase matrix (as shown in Fig. 4(d)). Close investigation of the cracks showed the cracks being discontinuous, suggestin that crack bridging occurred behind the crack tip.

　　Fig. 5 shows the fractographs of the three type microstructures of Ti-22Al-20nb7Ta alloy. For the lath microstructure, intergranular fracture occurred along the prior coarse $B2$ grain boundaries (as shown in Fig. 5(a)). For equiaxed and duplex microstructures, the fracture modes were mainly transgranular cracking with a lot ductile dimples (as shown in Fig. 5(b) and (c)).

4　DISCUSSION

4.1　Microstructure —properties relationship

　　The poor ductility of supper-transus processed and/or solutionized microstructures has been suggested to be a result of the thick primary-BCC grain boundaries that induce low-energy intergranular fracture. The equiaxed microstructure and duplex microstructure produced by sub-transus thermo-mechanical processing, however, exhibit a good balance of properties of RT tensile strength, elongation and elevated temperature strength. Careful consideration of both alloy composition and thermo-mechanical processing is required for controlling the constituent phase volume fraction, composition, morphology and grain size.
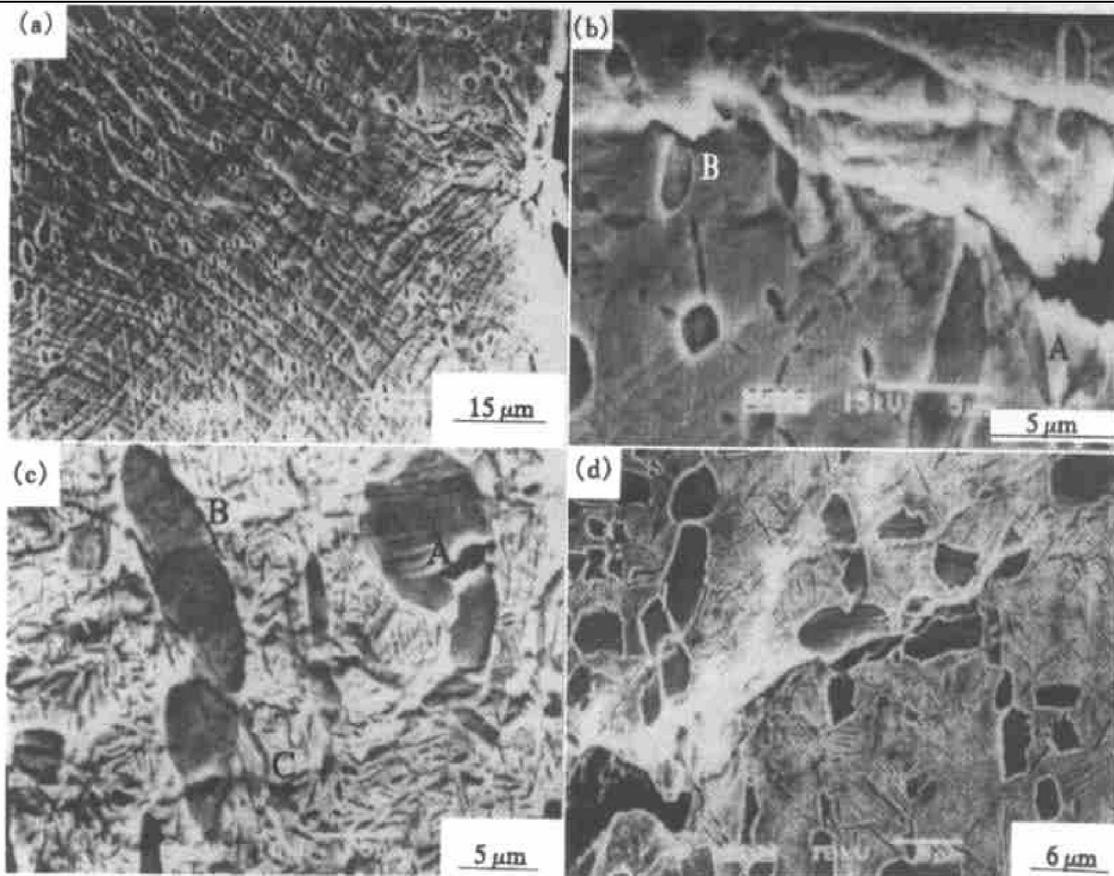
Fig. 4   SEM micrographs showing initiation and propagation of cracks in Ti-22Al-20Nb-7Ta alloy
(a), (b) —For equiaxed microstructures; (c), (d) —For duples microstructure
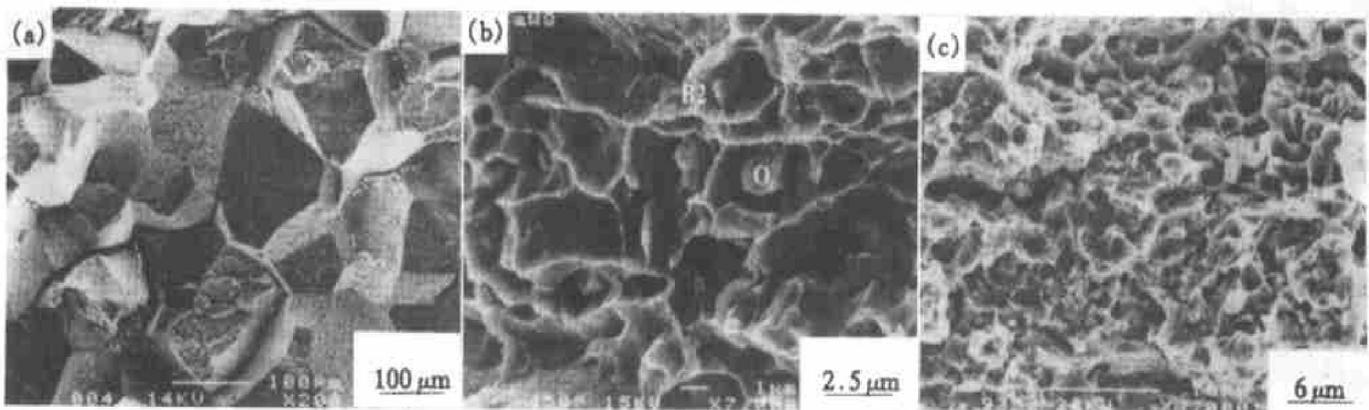

Fig. 5   Fractographic features of Ti-22Al-20Nb-7Ta alloys
(a) —Lath microstructure (TMP1 treatment); (b) —Equiaxed microstructure (TMP2 treatment);
(c) —Duplex microstructure (TMP3 treatment)

It was found that the basic strengthening mechanisms in orthorhombic alloys are similar to those in conventional titanium alloys. Boundary strengthening through microstructural refinement has the most important influence on strength and the secondary O lath sizes should be another important factor in strengthening, those of which can be attributed to a Hall-Petch type. In general, the uniform and fine quasi-equixed structure of (α_2 + $B2$ + O) or (O + $B2$) phases, with the grain size of about 2~ 3 μm, obtained through hot deformation in sub-transus (α_2 + $B2$ + O) or (O + $B2$) phases field, are beneficial to improve the tensile properties. The precipitation of fine secondary O laths with size of 1~ 2 μm from $B2$ matrix during aging at lower temperature in (O +

$B2$) phase field can increase the strength of orthorhombic alloy markedly while maintain a good RT ductility. It is the morphology of the secondary O laths that strongly controls ductility.

4. 2   Alloying strengthening effect

$B2$ phase strength was strongly dependent on comosition. Higher Al and lower Nb would led to increase of strength. The strength of equiaxed structures increases with the volume fraction of the $B2$ phase, suggesting that the $B2$ phase is stronger than α_2 or O phase. Boelert and Gogia[4, 5] have also shown that the strength of $B2$ phase is more strongly dependent on Al content than Nb content. Fully-O microstructures, based on the intermetallic composi-

tion of Ti_2AlNb, are brittle ($\delta < 1\%$) and has lower strengths (e. g. 700 MPa). When a sufficient volume fraction of the ordered $B2$ phase is present, elongation and strengths are greater than those for the fully-O microstructure. Thus a balance between strength and ductility must be maintained through proper alloying and selection of TMP treatment.

In quarternary alloy investigations, Rowe[6] discovered that small addition (up to 5%, mole fraction) of V a Ti-22Al-20Nb has proved to increase RT elongation values (up to 19%), but to result in the strength loss. Tang et al[7] have pointed out that addition of W or Mo could improve elevated temperature strength. In present work, addition of Ta partially replaced Nb to Ti-22Al-27Nb alloy, not only increased the strength of O and $B2$ phases individually through solid solution strengthening, but also increased the strength of ($O + B2$) matrix by refining the O phase laths. The results[10] showed the effect of addition Ta on the strength of O phase is double times than that of $B2$ phase. Consequently the strength of orthorhombic alloy, particularly the elevated yield strength, was increased markedly. The strength of Ti-22Al-20Nb-7Ta is higher by 20% than that of Ti-22Al-27Nb at 650 ℃ without any sacrifice in RT ductility. Thus quarternary Ta additions to improve the mechanical properties of near Ti_2AlNb alloys are attractive.

4.3 Role of microstructure in fracture

Contasting to the equiaxed microstructure, Ti_2AlNb alloy failed by a microvoid nucleation and growth along slip-band in $B2$ phase (as shown in Fig. 4(a) and (b)). In the lath microstructure, crack initiation and fracture were observed to occur along the primary $B2$ grain boundaries, indication large local stress concentration developed due to the strain incompatibilities at(or near) grain boundaries.

For the equiaxed microstructure many microvoids were formed in the areas related to the multi-slip-bands in $B2$ phase near the main crack tip, which resulted in a ductile fracture. For the duplex microstructure, three types of microcracks were observed in both the tensile and the fracture toughness specimens (as shown in Fig. 4(c) and (d)). Firstly, microcracks initiated in α_2/O particles. Secondly, microcracks formed along the interfaces of α_2/O and $B2$ matrix. Thirdly, microcracks initiated within the O phase lath alignments. Microcrack formation within α_2/O can be rationalized on a limited number of independent slip systems. The concentration of strains on the basal planes probably led to the slip band decohesion. The secondary O phase lath precip-

itates would also provide the microcrack nucleation as a result of the large difference in ductility between O and $B2$ phases. The ductile $B2$ phase can be beneficial for strain accommodation at the α_2/O grain boundaries and $O/B2$ interfaces in matrix, and thus can act as a barrier to arrest crack propagation. When a microcrack nucleates in an α_2/O grain or along the O lath, the ductile $B2$ allows the crack tip to blunt, deflect, and arrest the propagrating microcrack, as shown in Fig. 4(d). The $B2$ phase also blunts and deflects the macroscopic cracks and provides a ductile ligament (or bridge) which prevents easy linkage of microcracks with the main crack. The morphology of secondary O laths also strongly controls ductility of the orthorhombic alloy in duplex microstructure.

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