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Wrought processing of γ-TiAl alloys①

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[Abstract] The hot working behaviour of intermetallic titanium aluminide alloys was described. The microstructural evolution during hot working was systematically studied on a series of binary and technical alloys with aluminium contents ranging between 45% and 54% (mole fraction). Process regimes in terms of temperature and strain rate were identified which allow large strain hot working to be carried out, either by forging or extrusion, with the production of sound forgings. The major areas addressed in the paper are ingot structure and homogenization, factors determining hot working and recrystallization, ingot conversion, and secondary processing.

[Key words] titanium aluminides; hot working; dynamic recrystallization; grain refinement, microstructure

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1 INTRODUCTION

Intermetallic titanium aluminide alloys are an emerging class of materials that exhibit attractive thermophysical properties and thus offer interesting perspectives for applications in high temperature technologies. However, as other intermetallic compounds TiAl alloys suffer from brittle fracture, which often persists up to very high temperatures. Quality issues associated with ingot metallurgy are therefore of major concern for the fabrication and reliability of components. These involve shrinkage porosity, segregation of alloying elements, texture, and coarse microstructure. Attaining chemical homogeneity and refinement of the microstructure are therefore the most important prerequisites for the engineering application of intermetallic compounds[1]. To this end, large effort has been expended to establish wrought processing for TiAl alloys. In broad terms, the applied techniques bear a number of similarities to the processing of conventional materials. Yet titanium aluminides are generally more difficult to process due to their solidification behaviour, susceptibility to degradation from contamination, low diffusibility, reduced grain boundary mobility, and intrinsic brittleness. Thus, the identification of suitable processing conditions is difficult and requires a detailed understanding of the factors governing deformation, recovery and recrystallization. Investigation of these processes and their correlation with the alloy composition is the subject matter of the present paper.

2 ALLOY COMPOSITIONS AND INGOT STRUCTURE

The alloys investigated have the base line composition (mole fraction, %): Ti-(45~ 49)Al+ (0.3~ 5.0)X, where X designates modest amounts of several third elements, such as Nb, Cr, Mn, V, B, and C. Particular emphasis will be paid on high niobium containing alloys, because they have the potential to extend the service range of conventional titanium aluminide alloys[2]. The effects of the phase constitution on the hot working behaviour were investigated on a series of binary alloys with different Al contents. Compositions and microstructures will be specified for the examples presented. Ingots with diameter of 70~ 280 mm were produced by vacuum arc melting (VAR) and provided by different suppliers. In order to ensure a reasonable chemical homogeneity throughout the ingots the meltstocks were double- or triple-melted. The VAR ingots typically contained 0.01% ~ 0.03% nitrogen and 0.05% ~ 0.08% oxygen (mass fraction). Ingots with oxygen levels in excess of 0.12% are generally unacceptable for subsequent hot-working. Before wrought processing the ingots were hot isostatically pressed (HIP) in the ($\alpha+\gamma$) phase field at about 200 MPa for several hours in order to seal casting porosity.

In the composition range of Ti-(45~ 49)Al, which is the basis for engineering alloys, peritectic solidification and eutectoid reactions occur[3]. When these alloys are produced by conventional ingot metallurgy under relatively slow cooling a lamellar morphology may evolve which consists of thin parallel α_2 (Ti_3Al) and γ(TiAl) platelets. After solidification the γ platelets grow from the prior α grains with crystallographic alignment[4] according to $\{111\}_\gamma /\!/ (0001)_{\alpha_2}$ and $\langle 1\bar{1}0]_\gamma /\!/ \langle 11\bar{2}0\rangle_{\alpha_2}$.

The α phase lamellae that remain during cooling, subsequently transform to the α_2 phase at temperatures below the eutectoid temperature. This solidification pathway leads to the formation of a den-

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dritic structure of α_2 and γ lamellae and interdendritic regions of nominally single phase γ grains which are last to solidify from the melt. Fig. 1 shows the lamellar microstructure of a Ti-45Al-10Nb alloy observed by optical microscopy. Al-lean alloys containing β phase forming elements, such as Cr, Mo and W, under fast cooling often exhibit alternative decomposition paths leading to more complex microstructures[3].

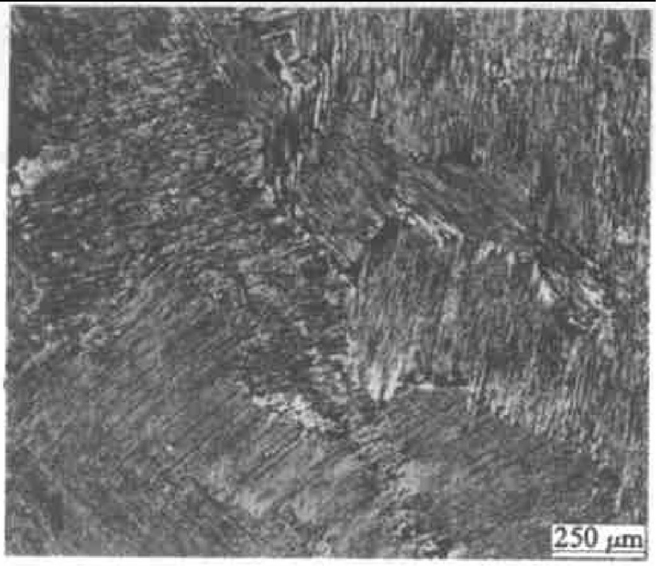

Fig. 1 Optical micrograph of Ti-45Al-10Nb alloy with nearly-lamellar microstructure

Longitudinal macro-sections of the as-melted ingots are usually characterized by large columnar grains growing inwards and upwards along the direction of heat extraction. The size of lamellar grains in as-cast alloys with 46% ~ 48% Al is typically 100~ 500 μm depending on cooling rate and, thus, ingot size. The lamellar platelets existing within the columnar grains have an orientation perpendicular to the long axis of these grains. Thus, the majority of individual columnar grains have lamellae arranged in a similar orientation, which results in a significant casting texture. The peritectic solidification reactions also give rise to an unavoidable micro-segregation, the extent of which depends on the nominal Al level and the content of refractory elements[5]. Al is rejected to the interdendritic region while refractory elements, in particular those stabilizing the β phase, are concentrated in the dendritic cores. The differences in content are as large as a few percent and vary on a length scale of about 1 mm[1, 2, 5~ 7]. Fig. 2 demonstrates these features observed on an ingot of the nominal composition Ti-45Al-10Nb. The microstructure consists of lamellar colonies formed at the prior α dendrites and interdendritic γ grains. Elemental EDX mapping [Fig. 2 (a) ~ (c)] and quantitative analysis [Fig. 2(d) ~ (f)] show that the interdendritic regions are rich in Al (49%) and depleted in Nb (7.5%). This compares with the values (45% Al and 10% Nb) determined in the dendritic cores. Rapid solidification processing generally reduces segregation, refines microstructure and, thus, produces a more homogeneous material consolidation. As ingot size increases, cooling becomes slower and the as-cast grain size increases, thereby exacerbating the problems associated with segregation. Heat treatments in the ($\alpha+\gamma$) phase field are mostly ineffective to mitigate the chemical gradients[1, 5~ 7]. Annealing in the α or ($\alpha+\beta$) phase field leads to significantly faster homogenization kinetics, but mostly results in rapid grain growth.

3 HOT-WORKING AND DYNAMIC RECRYSTALLIZATION

Apparently, the most critical step is to convert the coarse grained, textured and segregated microstructure into a more homogeneous and workable structure, that is suitable for secondary processing. The range of potential temperatures and strain rates for hot-working operations of ingot material were evaluated through compression testing of cylinders with volume of a few cubic centimeters followed by metallographic inspection. Flow curves determined on a Ti-47Al-4(Nb, Cr, Mn, Si, B) alloy at different temperatures and strain rates are shown in Fig. 3. Uniform deformation is characterized by a cylindrical specimen deforming to a cylindrical shape, with little bulging. Hot-working defects include cavities, internal wedge cracks and surface-connected cracks, which may lead to porous and cracked forgings. In this way workability maps for isothermal deformation were established, and these define a domain of uniform deformation by the absence of the failure modes mentioned above. Accordingly, forging operations can be carried out near the eutectoid temperature with strain rates up to $10^{-2}\ s^{-1}$. The flow stress response observed in this domain reflects the effect of dynamic recrystallization, in that the flow curves exhibit a broad peak at low strains ($\varepsilon \approx 10\%$), followed by flow softening to an ostensibly constant stress level at strains $\varepsilon = 60\% \sim 90\%$ (as shown in Fig. 3). Under these conditions the evolution of the microstructure occurs by thermally activated deformation and restoration processes, respectively, and thus depends on temperature, strain rate and strain. Likewise, the peak stress σ_p exhibits a systematic variation with testing conditions. The effects of strain rate and temperature are often incorporated into the Zener-Hollomon parameter[8]. The analysis of the experimental data leads to the impression that diffusion assisted non-conservative dislocation processes are strongly involved in hot-working of γ base alloys. It should be mentioned, however, that hot-working maps determined on relatively small compression samples cannot adequately reflect the problems associated with large-scaleforgings, such as die/work piece friction, heat losses or the development of secondary tensile

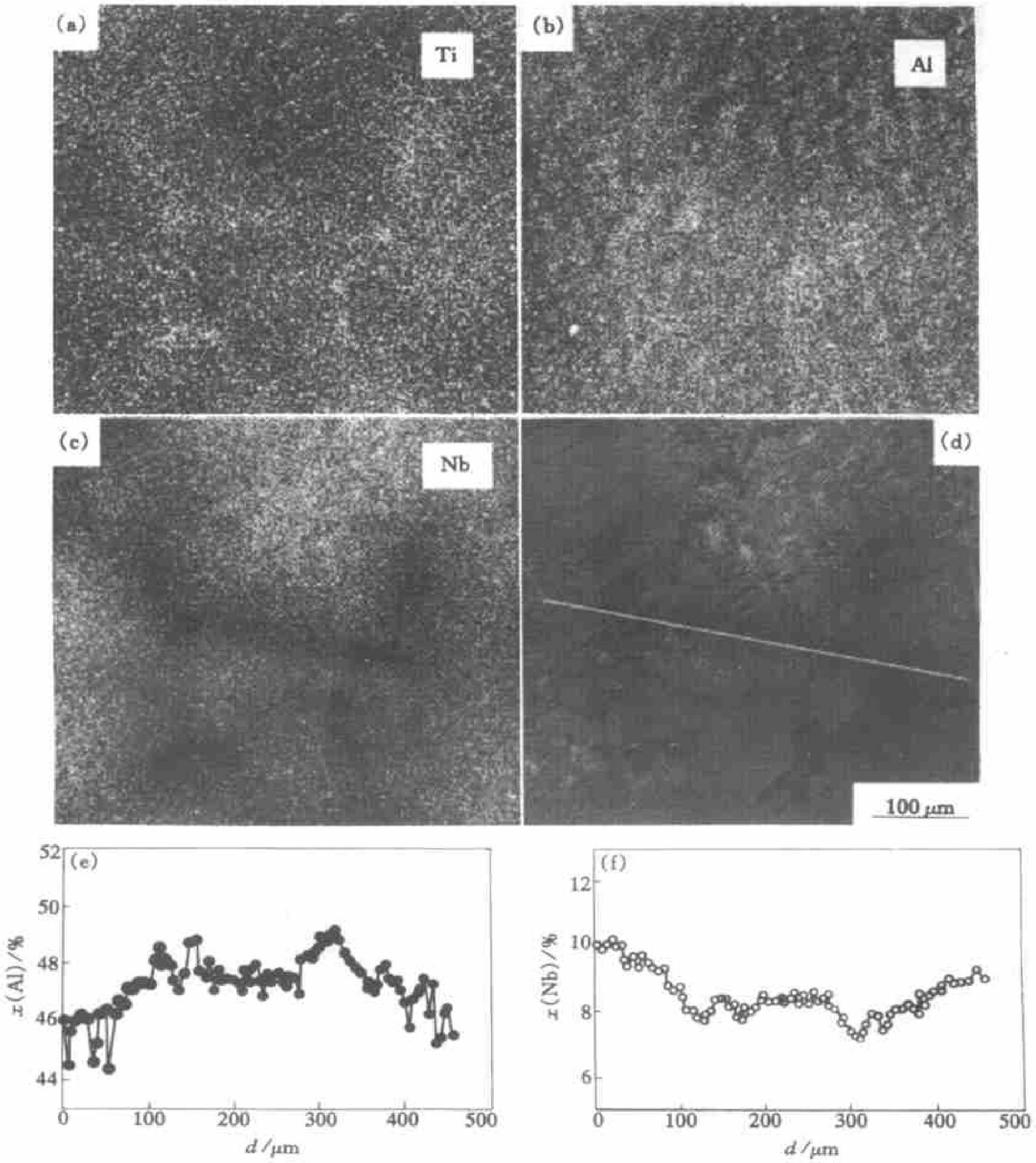

Fig. 2 Segregation pattern of 150 kg ingot with nominal composition of Ti-45Al-10Nb
(a) ~ (c) —X-ray maps showing elemental distribution of Ti, Al and Nb, respectively;
(d) —Back-scattered electron image of area shown in (a) ~ (c);
(e) and (f) —Variation of Al and Nb concentration along line indicated in (d)

stresses. Thus, up-scaling of wrought processing remains somewhat unpredictable.

Hot-working under the conditions mentioned above produces considerable refinement in the microstructure due to dynamic recrystallization and phase transformation. Recrystallization of ordered structures is expected to be difficult for mainly two reasons[9]. Firstly, the ordered state has to be restored and, secondly, there is a drastic reduction in grain boundary mobility, when compared with disordered metals. It is only recently that information on the atomic details of these processes has been obtained[10]. There is ample evidence that the spheroidization of the lamellar structure is supported by the propagation of ledges along the lamellar interfaces and pipe diffusion through the cores of grain boundary dislocations, which produces both the required change in the stacking sequence and local composition. Recrystallization was often found to be triggered by blocked twins, where high stress concentrations are expected to occur. In this respect, intersections of twins might be particularly important as these places provide both high stress concentrations and dense arrangements of defects[11].

The microstructural evolution has been systematically studied on a series of binary and technical alloys

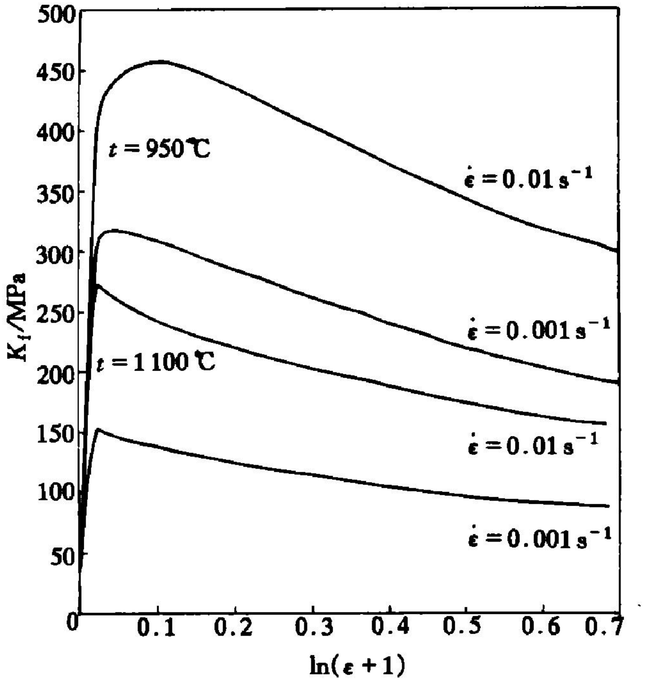

Fig. 3 Flow curves of cylindrical compression samples (d18 mm × 30 mm) of Ti-47Al-4(Nb, Cr, Mn, Si, B) alloy

with aluminium contents ranging between 45% and 54%[12]. Not surprisingly, the degree of dynamic recrystallization increases with strain, however, no substantial recrystallization occurs below strains of about 10%. There is also a marked effect of the aluminium content on the recrystallization behaviour, which is manifested in the observation that the recrystallized volume fraction is at maximum for aluminium contents of 48% ~ 50% (as shown Fig. 4). The recrystallization behaviour of two-phase alloys is also supported by the presence of boride particles[12]. Boron is known to significantly refine the as-cast microstructure[13], which is generally a good precondition for homogeneous hot working and recrystallization. In addition, particle stimulated dynamic recrystallization may occur, when dislocations are accumulated at the particles during hot working.

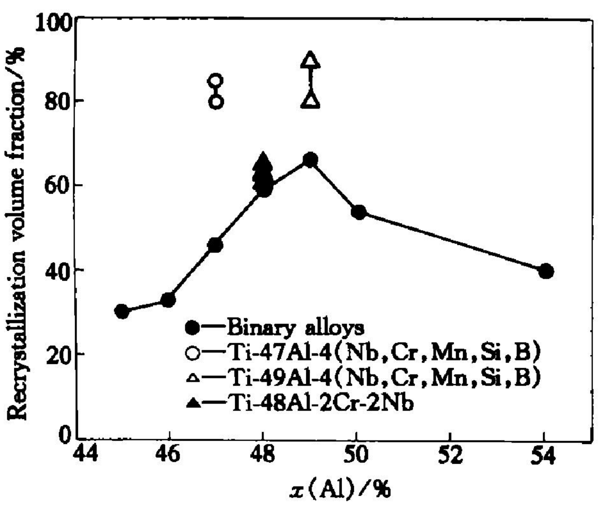

Fig. 4 Dependence of volume fraction of recrystallized grains on aluminium content of binary and technical alloys
(θ= 1 000 ℃; $\dot{\varepsilon}$= 5 × 10^{-4} s^{-1}, ε= 75%)

The Ti-rich alloys often have a coarse grained lamellar structure with colony sizes up to 2 mm. In these materials it has frequently been observed that highly localized shear bands are formed which often completely intersect the work piece. As has been described before, the shear bands consist of very fine equiaxed grains. Subsequent deformation may therefore preferentially occur by grain boundary sliding. Thus, outside the shear bands the amount of imparted strain energy is relatively low, which makes the recrystallization kinetics sluggish. These mechanisms not only result in an inhomogeneous microstructure, but often lead to premature failure of the work piece. Strain localization and shear band formation are therefore critical issues with regard to the hot working of γ base alloys.

4 PRIMARY INGOT BREAK-DOWN

Primary ingot break-down has been accomplished on an industrial scale utilizing forging or extrusion[2, 14]. Typical conditions for large-scale isothermal forging are θ= 1 000~ 1 200 ℃ at strain rates $\dot{\varepsilon}$ = 10^{-3}~ 10^{-2} s^{-1}. 50 kg-billets have been successfully forged within this processing window to height reductions of 5∶ 1 (as shown in Fig. 5). Edge cracking was usually minimal and surface appearance was good. The as-forged structure appears banded, consisting of stringers of α_2 particles in a fine grained γ matrix[1, 2, 14][as shown in Fig. 5(b)]. In two-phase alloys it is also common to observe lamellar colonies with lamellae lying in the plane of forging (as shown in Fig. 6). These colonies are probably undeformed remnants from the cast structure. Canning and thermal insulation of the work piece is very effective in order to avoid surface chilling and cracking[1]. This expands processing windows by decreasing the minimum temperature, increasing the highest strain rate, and increasing the maximum strain under which deformation without observable macroscopic failure occurs. Thus, by canned forging, a larger amount of strain energy can be imparted, which is certainly beneficial for homogeneous dynamic recrystallization. This results in a significant refinement of the microstructure, when compared with uncanned isothermal forging[2, 14]. However, even under these conditions recrystallization of the lamellar structure is incomplete. A more homogeneous refinement of cast microstructures can be achieved by two-step isothermal forging which involves an increment of static recrystallization due to an intermediate heat treatment.

Extrusion was carried out at temperatures around the α-transus temperature[2, 14]. Under these conditions (typically 1 250~ 1 380 ℃) severe oxidation and

Fig. 5 Isothermal forging for ingot break-down of two-phase TiAl alloy with composition of Ti-47Al-4(Nb, Cr, Mn, Si, B)
(a) —Pancake (d580 mm × 50 mm);
(b) —Optical micrograph
(Fracture toughnesses determined for crack propagation parallel and perpendicular to forging direction are indicated)

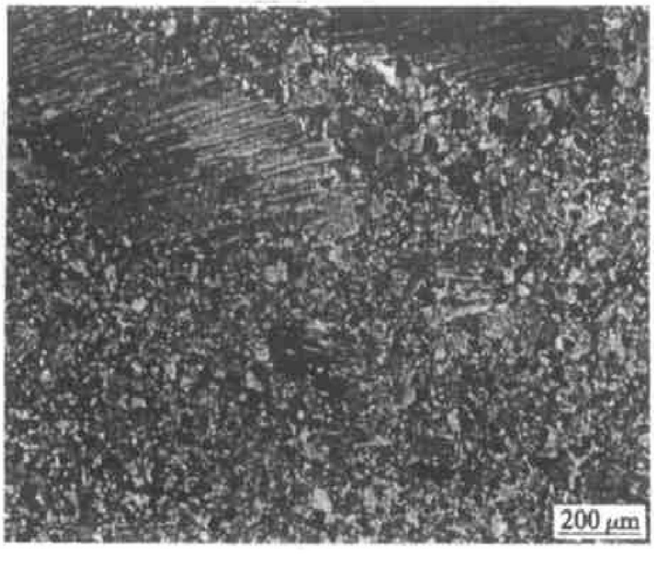

Fig. 6 Back scattered-electron micrograph of forged Ti-45Al-10Nb alloy
(θ= 1 100 ℃, $\dot{\varepsilon}$= 10^{-3} s^{-1}, ε= 65%)

corrosion occurs, thus, the work piece has to be encapsulated. In most cases conventional Ti alloys or austenitic steels are used as can material. At the extrusion temperature the can materials have a significantly lower flow stress than the TiAl billet[1]. This flow stress mismatch is often as high as 300 MPa and leads to inhomogeneous extrusion and cracking. These problems can largely be overcome by a novel can design utilizing radiation shields as an effective thermal insulation[15]. This reduces the heat transfer from the work piece to the can and enables controlled dwell periods between preheating and extrusion. Taking advantage of this concept, extrusion processes have been widely utilized for TiAl ingot break down. For example, 80 kg ingots were uniformly extruded into a rectangular shape with a reduction of the cross section of 10∶1 (as shown in Fig. 7). The alloy had the composition of Ti-45Al-10Nb and represents a new family of high strength materials that have been described in the previous section. Extrusion above the α-transus temperature (T_α) resulted in a refined nearly-lamellar microstructure with a colony size of 30 ~ 50 μm as demonstrated in Fig. 8(a). Extrusion below T_α led to duplex microstructures with coarse and fine-grained banded regions [as shown in (Fig. 8 (b)]. These structural inhomogeneities are associated with a significant variation in the local chemical composition, which is manifested at a length scale comparable to or slightly smaller than that of the as-cast material (as shown in Fig. 9). This observation provides supporting evidence that the dynamic recrystallization during hot working is strongly affected by local composition. The coarse-grained bands probably originate from the prior Al-rich interdendritic regions where no α_2 phase was present. Thus, grain growth following recrystallization is not impeded by α_2 grains. On contrary, the fine-grained bands or lamellar colonies are formed in Al-depleted core regions of the dendrites[16, 17].

The refined microstructure established after hot

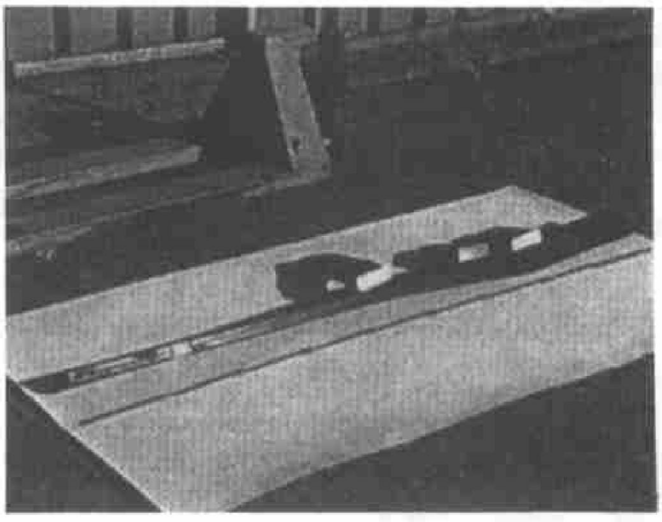

Fig. 7 Ingot break-down of an engineering alloy with base line composition of Ti-45Al-(5~ 10)Nb+ X by canned extrusion at T_α- ΔT

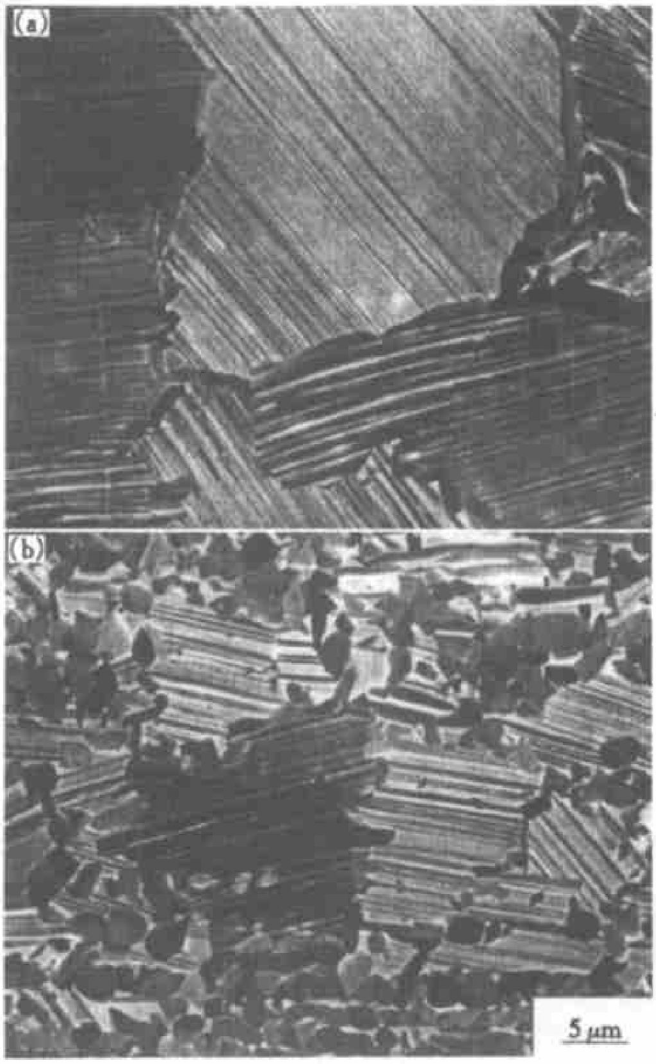

Fig. 8 Back-scattered electron images of Ti-45Al-10Nb alloy extruded at $T_{\alpha}+\Delta T$ to 7∶1 reduction
(a) —Nearly-lamellar microstructure;
(b) —Duplex structure with banded morphology

working generally results in a significant strengthening, when compared with cast material. The increase in yield strength can be rationalized in terms of Hall-Petch relations although quantitative descriptions are often difficult due to the complexity of the microstructures[2, 11]. Fig. 10 shows the dependence of the density compensated yield stress on temperature for forged and extruded γ base alloys, which have been developed at GKSS (Thyssen Umformtechnik Turbinenkomponenten GmbH). Extremely high yield stresses in excess of 1 GPa were obtained on Ti-45Al-(5~10)Nb derivative alloys after extrusion to a reduction ratio of 7∶1[2, 14]. For example for the alloy variant TNB-V (as shown in Fig. 8) at room temperature in tension a fracture stress of 1.1 GPa at a plastic strain of $\varepsilon = 2.5\%$ was determined. This combination of room temperature strength and ductility is the best ever reported on γ(TiAl) base alloys. Thus, this class of wrought TiAl alloys apparently provides an attractive alternative to conventional superalloys in an intermediate ranges of stresses and temperatures.

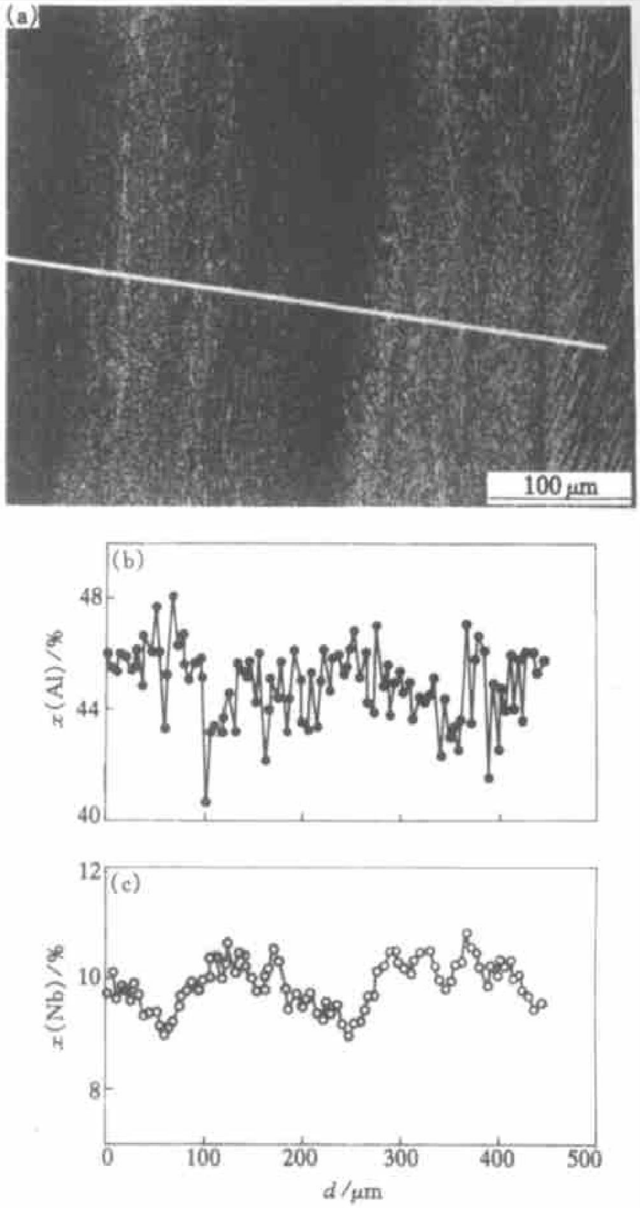

Fig. 9 Structural and chemical inhomogeneities of Ti-45Al-10Nb alloy extruded at $T_{\alpha}+\Delta T$ to 7∶1 reduction
(a) —BSE image showing duplex microstructure with a banded morphology;
(b) —Quantitative EDX analysis along line drawn in (a)

5 SECONDARY PROCESSING

Taking advantage of the refined microstructure, forged and extruded billets of different two-phase alloys including high niobium containing alloys with composition of Ti-45Al-(5~10)Nb were successfully processed in secondary operations, such as isothermal closed die forging and sheet rolling. For example, within the framework of a joint project together with the companies Thyssen Umformtechnik Turbinenkomponenten GmbH and Rolls-Royce Deutschland GmbH more than 200 turbine blades for the high-pressure aeroengine compressor were produced[14] (as shown Fig. 11). Ingot conversion was accomplished by canned extrusion below the α-

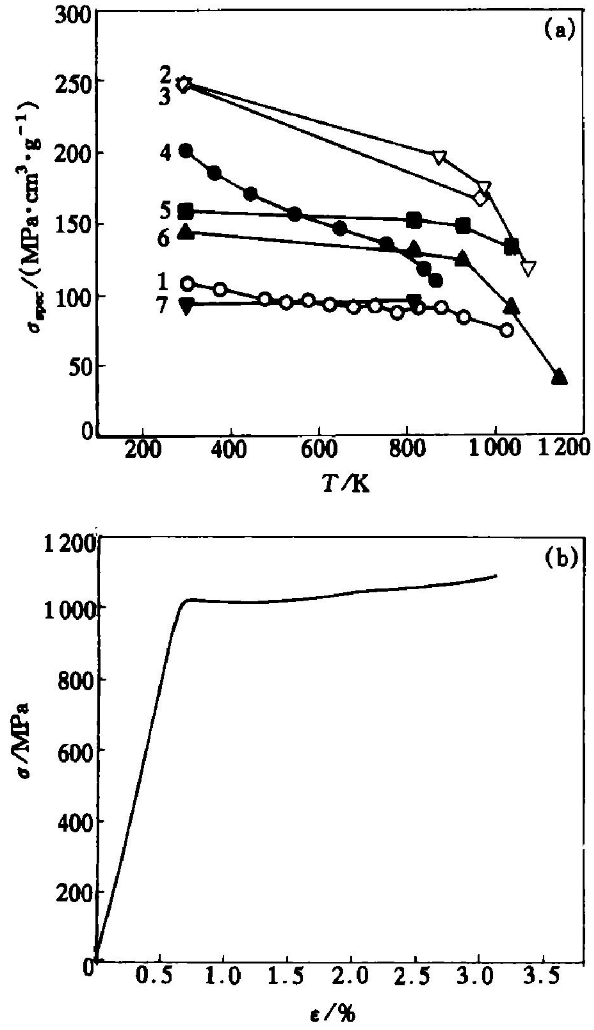

Fig. 10 Temperature dependence of density adjusted yield stresses for forged and extruded γ base titanium aluminide alloys (a) and load elongation test performed at room temperature on alloy 3 (TNB-V) (b)

(1 —Forged Ti-47Al-2Cr-0.2Si, near gamma microstructure; 2 —Extruded Ti-45Al-(5~10)Nb, duplex microstructure; 3 —TNB-V, Ti-45Al-(5~10)Nb+X, duplex microstructure; 4 —IMI 834; 5 —Réne 95; 6 —Inconel 718, 7 —IN 713 LC)

transus temperature. The blade geometry was produced by forging in the (α_2+ γ) phase field utilizing two sets of impression dies. After forging a substantial improvement of the microstructural homogeneity was observed both in the blade foil and the root when compared to the as-extruded material. The as-forged blades were subjected to a final heat-treatment at the α transus temperature followed by oil quenching, which resulted in a very homogeneous lamellar microstructure with a mean colony size of about 130 μm. The final shape of the blade was achieved by electro-chemical milling.

6 SUMMARY

Significant improvements in the chemical homogeneity and refinement of microstructure can be achieved by hot working and the associated dynamic recrystallization. There is an intimate correlation

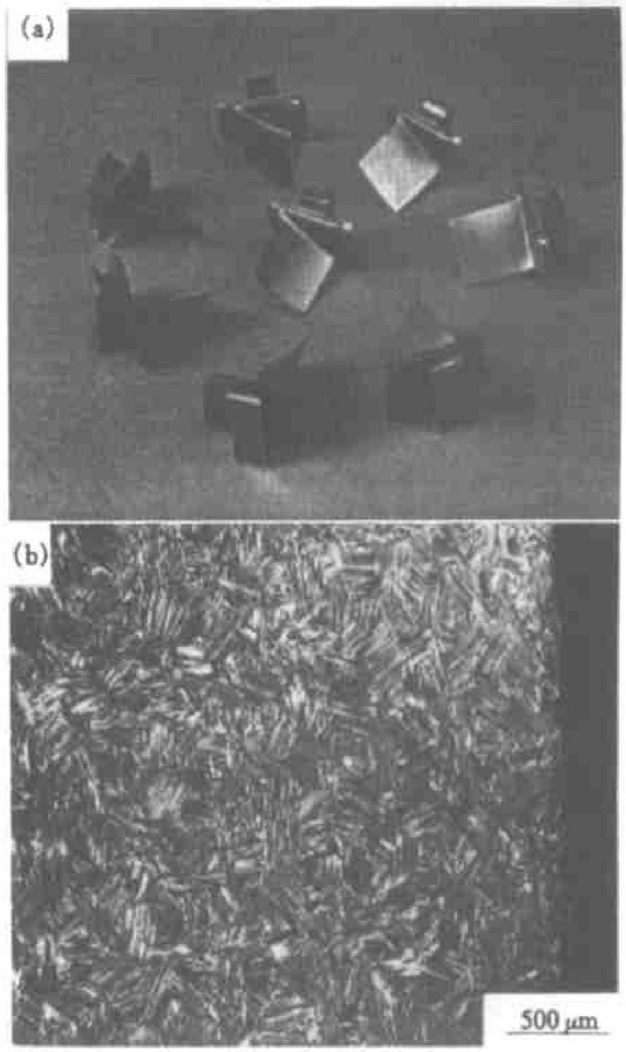

Fig. 11 High-pressure compressor blades for an aeroengine produced from a γ base titanium aluminide alloy by canned extrusion, two-step closed die forging and electro-chemical milling

between alloy chemistry, hot working conditions and the evolution of the microstructure, which has to be considered for wrought processing. In spite of the progress achieved in this field it must be admitted, however, that the processing of TiAl alloys is still a critical issue. Quality issues of primary processed products concern chemical and structural inhomogeneities, internal wedge cracks, and surface connected cracks. Thus, further improvement of hot working procedures is of major concern. In view of the results discussed above, this requires a tight optimization of the alloy composition and hot working parameters, respectively, and to find novel engineering solutions for increasing the amount of imparted strain energy, in order to achieve a more homogeneous recrystallization.

[REFERENCES]

[1] Semiatin S L. Kim Y-W, Wagner R, Yamaguchi M, ed. Gamma Titanium Aluminides [C]. TMS, Warrendale, PA, 1995. 509.

[2] Appei F, Oehring M, Wagner R. Novel design concepts

for gamma-base titanium aluminide alloys [J]. Intermetallics, 2000, 8: 1283–1312.
[3] Mccullough C Valencia J J, Levi C G, et al. Phase equilibria and solidification in Ti-Al alloys [J]. Acta Metall, 1989, 37: 1321–1336.
[4] Blackburnn M J. The Science, Technology and Applications of Titanium [M]. Pergamon Press, London, 1970. 633.
[5] Martin P L, Jain S K, Stucke M A. Kim Y-W, Wagner R, Yamaguchi M, ed. Gamma Titanium Aluminides [C]. TMS, Warrendale, PA, 1995. 727.
[6] Dimiduk D M, Martin P L, KIM Y-W. Microstructure development in gamma alloy mill products by thermomechanical processing [J]. Mater Sci Eng A, 1998, 243: 66–67.
[7] Mcquay P A, Simkins R, Seo D Y, et al. Kim Y-W, Dimiduk D M, Loretto M H, ed. Gamma Titanium Aluminides 1999 [C]. TMS, Warrendale PA, 1999. 197.
[8] Seetharaman V, Semiatin S L. Influence of temperature transients on the hot workability of a two-phase gamma titanium aluminide alloy [J]. Metall Trans, 1996, 27A: 1987–2004.
[9] Cahn R W, Takeyama M, Horton J A, et al. Recovery and recrystallization of the deformed, orderable alloy $(Co_{78}Fe_{22})_3V$ [J]. Mater Res, 1991, 6: 57–70.
[10] Appel F, Oehring M, Ennis P J. Kim Y-W, Dimiduk D M, Loretto M H, ed. Gamma Titanium Aluminides 1999 [C]. TMS, Warrendale, PA, 1999. 603.
[11] Appel F, Wagner R. Microstructure and deformation of two deformed, orderable alloys $(Co_{78}Fe_{22})_3V$ [J]. Mater Sci Eng, 1998, R22: 187.
[12] Imayev R M, Salishchev G A, Imayev V M, et al. Kim Y-W, Dimiduk D M, Loretto M H, ed. Gamma Titanium Aluminides 1999 [C]. TMS, Warrendale PA, 1999. 565.
[13] Hyman M E, Mccullough C, Levi C G, et al. Evolution of boride morphologies in TiAl-B alloys [J]. Metall Trans, 1991, 22A: 1647–1672.
[14] Appel F, Brossmann U, Christoph U. Recent progress in the development of gamma titanium aluminide alloys [J]. Advanced Engineering Materials 2, 2000. 699–720.
[15] Appel F, Lorenz U, Oehring M. Germany patent DE 1974257 [P]. 1997.
[16] Bartolotta P A, Krause D L. Kin Y-W, Dimiduk D M, Loretto M H, ed. Gamma Titanium Aluminides [C]. TMS, Warrendale PA, 1999. 3.
[17] Clemens H, Kestler H. Progressing and applications of intermetallic gamma-TiAl-based alloys [J]. Advanced Engineering Materials, 2000, 551–570.

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