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Characterization on hot deformation behavior of Ti-22Al-25Nb alloy using a combination of 3D processing maps and finite element simulation method

Yu Sun [a, b], Xiaoyun Feng [a, b], Lianxi Hu [a, b, *], Heng Zhang [a, b], Hongzhi Zhang [a, b]

[a] *National Key Laboratory for Precision Hot Processing of Metals, Harbin Institute of Technology, Harbin, 150001, PR China*
[b] *School of Materials Science and Engineering, Harbin Institute of Technology, Harbin, 150001, PR China*

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A B S T R A C T

In hot deformation behavior, two indispensable parameters which are power dissipation efficiency (η) and flow instability domains (ξ) in the processing maps have been exploited in most of literatures. However, rarely caught sight of dynamic distribution of η and ξ. In this study, hot deformation behavior of Ti-22Al-25Nb alloy was investigated by using a combination of three-dimensional (3D) processing maps and finite element (FE) simulation to unveil the variations of η and ξ with temperature, strain and strain rate during hot forming process. The hot compression tests were performed in the temperatures range of 995–1075 °C and strain rates from 0.001 to $1.0s^{-1}$. According to the basic experimental data of isothermal compression tests, the intrinsic workability relevant to this alloy was evaluated comprehensively on the basis of true stress-strain curves and 3D processing maps. Moreover, the recommended processing domains are predicated to be within the temperatures range of 1050–1065 °C and strain rates range of $0.01–0.1s^{-1}$, with a peak efficiency of 55%. The results of FE simulation show spatial distribution regularities of η and ξ in the specimens corresponding to the three characteristic districts during compressive deformation process. In addition, microstructure observations indicate a reasonable correspondence between hot processing parameters and microstructure evolution.

1. Introduction

Advanced aero-engine and automotive engine rely on high performance materials to enable increased performance. Improvements in vehicle structure and fuel efficiency that lower specific fuel consumption and lower CO_2 emission require higher temperatures, and drive the need for materials that are able to withstand those higher temperatures. Titanium aluminide (Ti_3Al) has been considered as one of this kind of materials due to their superb high temperature mechanical properties, good oxidation resistance, and high specific strength. However, as an intermetallic alloy, it is generally brittle, low toughness and poor processability, for example, it is very difficult in manufacturing the structure with complex shape due to its poor workability. It has been reported [1] that workability of the can be significantly improved by adding Nb into Ti_3Al based alloys. Banerjee et al. [2] initially identified a ternary intermetallic based on an ordered O phase with the orthorhombic structure, whose stoichiometry is Ti_2AlNb. Numerous efforts on Ti_2AlNb-based alloys have been made in order to improve their processability in recent years. As a part of these efforts, the Ti-22Al-25Nb alloy, the second generation of an orthorhombic alloy, has been under continuous development as a promising candidate, owing to its excellent mechanical property, for instance good combination of strength and elongation-to-failure, excellent creep resistance [3–6] having attracted considerable attentions of researchers worldwide. Even through some significant improvements of the Ti-22Al-25Nb alloy has been achieved compared to the original Ti_3Al alloy, the Ti-22Al-25Nb alloy still fills into the family of difficult to process materials including hot forming processing because of its poor plasticity.

In term of hot forming processes of materials, flow behaviours of material are fairly complex because the hardening and softening mechanisms exert significantly influences on the deformation behavior of material. Furthermore, these mechanisms are sensitive to the processing parameters, such as deformation temperature (T),

* Corresponding author. National Key Laboratory for Precision Hot Processing of Metals, Harbin Institute of Technology, Harbin, 150001, PR China.
E-mail address: hulx@hit.edu.cn (L. Hu).

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strain (ε) and strain rate ($\dot{\varepsilon}$). The determination of proper hot working parameters is critical in pursuit of obtaining the optimum hot working process. Therefore, it is imperative to construct a hot processing map to identify the reasonable processing window of the Ti-22Al-25Nb alloy.

The processing map is regarded as a powerful tool to evaluate workability for steels [7,8], magnesium alloys [9–11], aluminium alloys [12,13] and titanium alloys [14–16]. Frost and Ashby et al. [17] described the reaction of material to processing parameters at the earliest by the Deformation Mechanism Map, which is suitable to lower strain rates on the basic of creep mechanisms. Considering the direct effects of strain rate ($\dot{\varepsilon}$) and deformation temperature (T) on material processing, Raj et al. [18] combined the atomistic method with basic parameters to establish Raj's maps via expanding the concept of Ashby's Map. However, the processing map of Raj is limited to pure metals and dilute alloys, resulting in that, it is not applicable for most commercial alloys. Prasad et al. [19] proposed the most widely-used processing maps, which not only illustrate the microstructural evolution mechanism as well as the flow instability areas at certain conditions but also optimize the strain rate ($\dot{\varepsilon}$) and deformation temperature (T). Since then, the processing maps based on the dynamic materials model (DMM) and Prasad instability criteria have been used to elucidate the processability of materials with very limited algorithmic changes but some minor variations of the mapping method as the computer technology advances fast. The traditional processing map can be constructed at a certain strain by two-dimensional (2D) diagrams, which does not refer to the variation of strain. Zhang et al. [20] and Quan et al. [21] separately studied the deformation behavior as well as microstructure evolutions of Ti-22Al-25Nb and Ti-6Al-2Zr-1Mo-1V alloys, and determined the optimized working domains according to the built 2D processing maps at a series of strains. In fact, 2D processing map does not present a continuous effect of strain, therefore it limited on assessing the influence of strain rates and temperatures on materials forming at a series of strains. A few of researchers work forward to establish continuous 3D processing maps in order to unveil the hot workability of materials. Liu et al. [22] for the first time constructed the 3D processing maps of AZ31B magnesium alloy by conducting the Gleeble-1500 thermo-mechanical tests and analyzed its state-of-stress workability with finite element simulation (FEM). Mohamadizadeh et al. [23] and Sun et al. [15] identified the optimal processing parameter windows of a low-density steel as well as TiAl-based alloy respectively by plotting 3D processing maps, and analyzed the difficult degree of materials forming to then evaluate the hot workability by using activation energy maps. Results above are attaching importance to the entire material, whereas, very few researchers investigate characteristic parameters of the processing maps utilizing finite element simulation. It can realize not only a dynamic visual representation of these parameters but also the visualization of their distribution in different deformation areas of the samples.

In the present work, 3D processing maps based on DMM and Prasad instability criteria are established to demonstrate the effects of different processing parameters on power dissipation efficiency (η) and flow instability factor (ξ). Results are analyzed by combining the microstructure observations of various characteristic zone in processing maps. By constructing the functional equation between characteristic parameters and processing ones, the secondary development of FEM are implemented to reveal the distribution situation of η and ξ in hot compression specimens.

2. Material and experimental procedures

The research material in the present study was determined to be a Ti-22Al-25Nb (at%) alloy billet, which is fabricated by high-energy milling pre-alloyed powders prepared by argon gas atomization and subsequently hot pressing. Ball-milling process was carried out with ball-to-powder weight ratio of 40:1 at a rotate speed of 400 rpm for 2 h. Hot deformation was conducted in graphite dies at 1100 °C/50 MPa/1 h in high vacuum followed by furnace cooling. Fig. 1 shows the X-ray diffraction pattern of the billet. It can be found that the phases of the initial material consist of α_2 phase, B2 phase and O phase. The initial microstructure is emerged in Fig. 2. It can be seen from this figure that the initial billets are composed of typical three-phase microstructure where a fraction of lamellar O phases participate in B2 grains and an amount of α_2 phases distribute along B2 grain boundaries.

The cylindrical specimens with a diameter of 6 mm and a height of 9 mm were machined from the hot-pressed billet. They were cut uniformly along their cylinder axes parallel to the hot pressing direction to ensure the homogeneous performance. The isothermal compression tests were carried out on a Gleeble-1500D thermo-mechanical simulator in the temperatures ranging from 995 to 1075 °C with an interval of 20 °C and four strain rates from 0.001 s^{-1} to 1.0s^{-1} with the interval of an order of magnitude. The graphite lubricant was applied to minimize the effect of deformed friction at the interface of punch and specimen during the hot deformation. Prior to compression, all specimens were heated up to a preheat temperature of 900 °C with the rate of 15 °C/s, thereafter kept being warmed to the deformation temperature at a 10 °C/s rate and soaked for 3 min to eliminate thermal gradients. The compressive deformation tests were conducted up to a total true strain of 0.65 at a constant strain rate, followed by water quenching immediately to room temperature for retaining the deformed microstructure at elevated temperature. The deformation temperatures were monitored by a thermocouple as well as the variations of stress and strain were measured continuously by an automatic data acquisition system with a matched computer. The schematic illustration of the hot compression tests is shown in Fig. 3. All deformed specimens were cut in the center parallel to the longitudinal compression direction in the pursuit of examining the microstructure evolution of Ti-22Al-25Nb alloy during compression deformation using optical microscope (OM). For optical observation, the specimens were treated with grinding, mechanical polishing and chemical etching in a Kroll reagent of 1 ml HF, 3 ml HNO_3, 10 ml H_2O. In order to observe the initial microstructure of alloy and further verify the distribution of phase, scanning electron microscope (SEM) and Electron Back-Scattered Diffraction (EBSD) technique were employed as shown in Fig. 1. The preparation method of

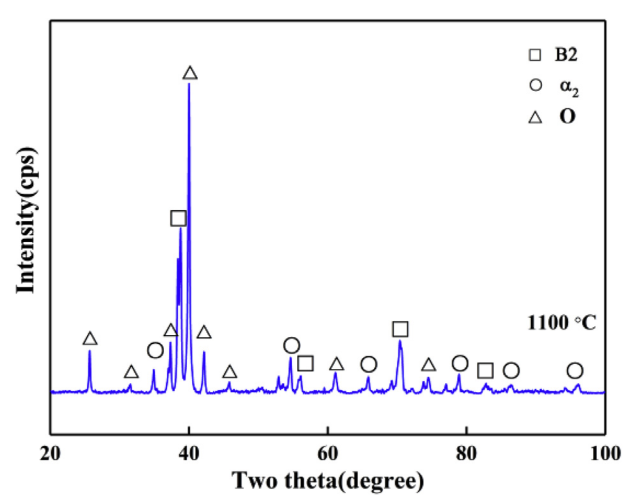

Fig. 1. X-ray diffraction pattern of Ti-22Al-25Nb billet.