Study on the deformation behavior of multi-pass hot compression for EBCHM single casting TA1 slab

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Abstract: In this paper, multi-pass hot compression experiments of pure titanium TA1 were investigated with Gleeble-3500 thermal simulation test machine at an initial temperature of 880℃. The purpose is to investigate the effects of hot compression on the deformation of an electron beam cold hearth melting (EBCHM) single casting TA1 slab. The microstructure of the sample was analyzed by metallography and electron backscatter diffraction (EBSD), and the dynamic recovery was found to be the main recovery mechanism. The recrystallization nucleation mechanism were mainly bulging at grain boundary and merging of sub-grain.

1. Introduction
Titanium and titanium alloys have various properties, including high strength, high temperature resistance, high damping, decent corrosion resistance, good biocompatibility and superconducting properties. They are widely used in aerospace and chemical petroleum, automotive, medical and civil construction[1]. After more than 70 years of development, the global titanium industry has flourished, and the United States, Japan, Russia and China have become major countries in the titanium industry[2]. Titanium and titanium alloys are pivotal structural materials, and the development of which have received worldwide attention.

Some of the following aspects are focused recently on the deformation behavior mechanism of pure titanium: Sheikh-Ahmad[3] used the Johnson-COOK model to explain the mechanism of shear force generation during deformation. Chou et al. [4] studied the effects of temperature and strain rate on the compressive mechanical behavior of pure titanium and introduced the Kocks-Mecking model. Nematnasser et al. [5] established a new constitutive model of pure titanium from the dislocation slip angle to describe the correlation between temperature and strain rate during plastic deformation of pure titanium. Zhou et al. [6] studied the effects of temperature, strain and strain rate on the plastic deformation behavior of materials through a numerical methodology. The rapid development of analytical techniques in recent years has greatly contributed to the study of material properties. Chichili et al. [7] performed dynamic torsion and compression experiments of pure titanium using the compression-torsion Kolsky bar and TEM, and found that the microstructure evolution in pure titanium during deformation. Li et al. [8] established the hot processing map of pure titanium TA1 through thermal simulation experiments.

In recent years, great progress was made in the study of deformation theory, but there are still many unsolved problems for industrial applications. It should be noticed that titanium is a chemically active
element and is also a difficult-to-cut metal. The key for expanding the application of titanium is to improve the processing and molding of pure titanium \[^9-11\]. At present, titanium plate accounts for more than 50% of the total titanium production, and the most accepted coil-rolled process is limited by the high cost, long producing cycle caused by forging. In recent years, with the application of large furnace (EBCHM furnace) in China, it is possible to directly roll large-scale titanium strips with single casting slabs. This application will effectively reduce the production process and the cost.

However, the deformation processing is absent for the production of EBCHM single casting slabs, which will lead to considerable microstructure difference compared to forged slab and will affect the subsequent rolling process technology. In this paper, the effects of hot compression on the deformation of a EBCHM single casting TA1 slabs are studied by multi-pass hot compression experiments. The purpose is to provide practical reference for titanium producers.

### 2. Materials and methods

The industrial scale TA1 pure titanium slab is directly produced with EBCHM by a Chinese titanium producer. After wire-electrode cutting, the Φ10×15 cylindrical samples were produced for the subsequent tests. The chemical composition of the produced TA1 sample is shown in Table 1.

| Element | N  | C  | H  | Fe  | O  | Ti  |
|---------|----|----|----|-----|----|-----|
| Content | ≤ 0.01 | ≤ 0.01 | ≤ 0.003 | ≤ 0.02 | ≤ 0.06 | margin |

Table 2. Experimental scheme of multi-pass hot compression.

| Deformation temperature (°C) | Deformation (%) |
|-----------------------------|-----------------|
| 860                         | 25 25 25 20 15  |
| 840                         | 25 25 25 20 15  |
| 820                         | 20 20 10 10 10  |
| 800                         | 20 10 10 10 10  |
| 780                         | 20 10 10 10 10  |
| ∑71.2                      | ∑63.5 ∑58.9 ∑53.3 ∑47.3 |

The prepared sample was then subjected to multi-pass hot compression tests by Gleeble-3500 thermal simulator. The thermocouple wire was heated to 880°C at a heating rate of 10°C/s. After 5 min of heat preservation, the experiment was carried out according to the process scheme shown in Table 2.

There were totally five passes for the multi-pass hot compression deformation (strain rate 1s\(^{-1}\)), the cooling rate of the pass interval was 5°C/s, after the fifth pass, the samples were quickly taken out for water cooling to maintain the deformed microstructure. During the experiment, the true stress-strain curve was drawn by Origin software after the test, and the flow stress of TA1 under different process parameters was studied. After the sample was buffed, polished, and etched, the microstructure was analyzed by metallographic microscope and EBSD.

### 3. Results and Discussions

#### 3.1. Flow stress

The true stress-strain curve and the peak stress change diagram of TA1 under different deformations are shown in figure 1 and figure 2, respectively.
Figure 1. Stress-strain curve under different shape variables. (a) 71.2%; (b) 63.5%; (c) 58.9%; (d) 53.3%; (e) 47.3%

Figure 2. Peak stress at different deformations.

The results in figure 1 indicate that the maximum peak stress appears in the fifth pass. For the total deformation of 71.2% and 47.3%, the peak stress is 158.4 MPa and 90.96 MPa, respectively. Apparently, the compression pass has little effect on the flow stress of the material, whilst the flow stress is dominated by the deformation. If the total deformation is fixed, the deformation of each pass decreases with the increasing passes of deformation. Consequentially, the material flow stress decreases.
3.2. Microstructure

![Figure 3. Organizational topography under different shape variables.](a) 71.2%; (b) 63.5%; (c) 58.9%; (d) 53.3%; (e) 47.3%]

Figure 3 shows the metallographic structure of the sample at different deformations. After multi-pass of deformation, the original grain are perpendicular elongated to the compression direction, and become flattened, and serious grain breakage appears. Some of the jagged grain boundary is found with a bow-bend shape. The results indicate that dynamic recovery occurs during the deformation. In figure 3 (d) and (e), some fine grains appear in the vicinity of some large grain boundaries, it indicates that dynamic recrystallization may occur during the deformation process. However, there is no obvious stress drop on the true stress-strain curve in Figure 1, so it is impossible to judge whether it is a recrystallized grain generated by dynamic recrystallization, because recrystallized grains may also be formed in the pass interval. Figures 4 (a) and (b) show that the deformed grain size is relatively large, and the grain boundary bow appears more prominently, but the fine grains are less. This indicates that the recovery mechanism of TA1 at high temperature deformation is mainly dynamic recovery, when the deformation increases, dynamic recrystallization occurs in some grain boundaries.

3.3. Inverse pole figure (IPF) analysis

![Figure 4. IPF diagram under different shape variables. (a) 71.2%; (b) 47.3%](a) 71.2%; (b) 47.3%

Figure 4 shows the EBSD microstructure with a total deformation of 71.2% and 47.3%. The grains after hot compression of different deformations show a state of fracture and reorganization, and the EBSD reorganization phenomenon is more obvious when the deformation is 71.2%. The deformation
is leading to a high dislocation density which resulting in twin nucleation and a large number of sub-grain-cutting original grains.

3.4. Recrystallization quantitative analysis

Figure 5 is a graph showing the recrystallization ratio with the total deformation of 71.2% and 47.3%. In the figure, red indicates a deformed grain with a grain orientation difference of 7.5-15°; yellow indicates a sub-grain with an orientation difference of 7.5-15°; blue indicates a recrystallized grain with a grain orientation difference of less than 2°. When the deformation is 47.3%, the recrystallized grains and sub-grain integral numbers are 3.9% and 42%, respectively. When the deformation increases to 71.2%, volume fractions of the two are 5.8% and 22%, respectively. Although the recrystallization ratio is low, the recrystallization improves with the deformation ratio. This is because the nucleation on the bulging of serrated grain boundaries. More dislocations during plastic deformation at high temperature will lead to dislocation walls at the grain boundaries. The dislocations are entangled with each other. During the quenching process, the deformed grains partially transform into substructures, and the substructures grow up to form recrystallized grains. Combined with the experimental results of multi-pass true stress-strain curve, the recovery mechanism in the single-pass compression process is mainly dynamic recovery, no obvious recrystallization characteristics, so the recrystallization ratio in the multi-pass compression process is small.

3.5. Smith factor analysis

Figure 6 is a Smith's factor analysis chart (SF) with a deformation of 71.2% and 47.3%. In the color gradient diagram, the Smith's factor of the red grain is the largest, and the Smith's factor of the blue
grain is the smallest. The figure shows that the color of the grain structure is complicated, and the color of the tissue varies greatly depending on the deformation. The slipping ability of TA1 is affected by the deformation. The larger the deformation, the easier for slip. The Smith factor of TA1 is not only affected by the deformation, but also related to the lattice structure of pure titanium. The analysis of the grain boundary diagram shows that the larger the deformation, the larger the proportion of the small-angle grain boundary, which further confirms that the deformation will affect the slip actuation. The average value of the Smith factor is 0.679, 0.546, respectively. It can be seen that the Smith factor value is relatively large, which indicates that the grain rotation and the grain boundary migration have been going on during the deformation process. At a certain strain rate, the larger the deformation, the higher the energy storage at the grain boundary, and the grain also rotates to a specific direction. Therefore, the orientation is preferred as shown in figure 6. The grain boundary migration phenomenon becomes significant with the increased amount of deformation. The grain orientation is chaotic when the deformation is 49.6%. When the deformation is 71.2%, the grain orientation is perpendicular to the compression direction, the Smith factor value is larger and more conducive to slip.

4. Conclusions
(1) The true stress-strain curves of different deformations are plotted by multi-pass hot compression experiments. It can be seen from the curve that the deformation will affect the flow stress of the material under multi-pass hot compression conditions. The larger the deformation, the greater the flow stress of a single-pass.

(2) The recovery mechanism of pure titanium TA1 in multi-pass hot compression process is mainly dynamic recovery and dynamic recrystallization assisted deformation. After deformation, deformed grains and sub-grains are the mainly microstructure in the pure titanium TA1 sample.

(3) The deformation ratio has great influence on the proportion of recrystallized grains. Larger deformation ratio will lead to more recrystallization during hot compression.

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