Microstructure and Mechanical Properties of a Rolled Ti–Si–B Alloy


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In order to obtain the Ti–Si–B alloys with uniform and fine microstructure, the hot workability of Ti–Si–B alloys was investigated by rolling method. The influence of deformation on the microstructure and mechanical properties was studied using optical microscopy, SEM, EPMA and mechanical properties testing. Results show that the alloys exhibit good thermal plasticity from 773 to 1173 K. The deformation induced a significant refinement of microstructure of Ti–Si–B alloys. Both tensile strength and ductility were improved through rolling deformation. The elongation of Ti–0.5Si–0.2B alloy was up to 25.7% and the tensile strength is about 828 MPa when the alloy was rolled with reduction of 50% at 1173 K. Relatively lower rolling temperature can improve the microstructures and mechanical properties of the titanium alloys more effectively.

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1. Introduction

Titanium alloys are widely recognized for their excellent combination of high strength, low density and high corrosion resistance. The composite materials of titanium alloys are expected to have appreciable improvement in elastic modulus, strength, wear resistance, high temperature capability and physical properties than monolithic alloy by combining the high strength and stiffness of a ceramic.1) TiB is well suited for reinforcement of titanium alloys because of a narrow region of solid solution between titanium and boron.2,3) A considerable amount of research 4–7) has been performed used to produce in-situ titanium matrix composites reinforced with TiB whiskers by ingot metallurgy and rapid solidification processing powder metallurgy techniques. Some investigators8,9) have revealed that the creep resistance of titanium alloys is improved by a small amount of silicon addition due to the precipitation of silicide on mobile dislocation resulting in a pinning of these dislocations and inhabitation of their further movement.

In our previous study,10,11) it has been found that a small amount of boron and silicon addition induces a significant refinement of as-cast structure and improvement of mechanical properties. Cast Ti–0.5Si–0.2B and Ti–0.2B alloys display relatively higher strength and ductility. However, the existence of casting defects such as internal porosity, marginal integrity and segregation is harmful to the quality of titanium alloys. The hot working operations are good ways to develop a titanium alloy with fine and uniform structure. Several investigators12–15) studied the hot workability of titanium and aluminium alloys. It can be deduced that a fine microstructure with TiB and Ti₅Si₃ dispersed homogeneously in the titanium matrix may have good mechanical properties and wear resistance.

The object of the present paper is to evaluate hot-workability of the Ti–0.5Si–0.2B and Ti–0.2B alloys. The discussion will cover the effect of rolling reduction and temperature on the mechanical properties and microstructure of rolled titanium alloys. The results are essential in developing the hot-working technology of the ceramic reinforced titanium alloy.

2. Experiment Procedure

The Ti–0.5Si–0.2B and Ti–0.2B alloy ingots were fabricated using an arc melting casting machine as our previous studies.10,11) The obtained as-cast ingot was a rectangular one with a dimension of approximately 45 × 20 × 12 mm³. The chemical compositions of elemental materials used in this study were summarized in Table 1. The ingot was sliced into billet with a size of 40 × 10 × 7 mm³. The billets were subjected two kinds of thermo-mechanical treatment. First, the billets were hot-rolled in a reduction of 30%, 50% and 70% after heating at 1173 K, which used to evaluate the influence of reduction on the microstructures and mechanical properties of Ti alloys. Second, the billets were rolled at 573 K, 773 K, 973 K and 1173 K to 3.5 mm (50% reduction) to assess the effect of deformation temperature. Each time the billets were compressed in 0.5 mm, then the billets were heated again in 5 min for next rolling. Thus, the reduction was total reduction in this study.

The flat tensile test specimen with a gauge length of 10 mm, width of 2 mm and a thickness of 0.5 mm were cut from as-rolled plate along the rolling direction by electro-discharge machining. The tensile test was performed using an Instron-type machine at an initial strain rate of 5 × 10⁻² s⁻¹ at room temperature. The specimens for metallographic examinations were ground with silicon carbide papers from 220 to 2400-grit, and polished with a nylon or a silk cloth using 6- to 1-μm diamond spray. After being cleaned with acetone and ethanol using an ultrasonic washer, the specimens were etched with a solution containing 5 mL HF, 20 mL HNO₃ and 75 mL H₂O. The deformed microstructures were examined by an optical microscope, and an electron probe microanalyzer (EPMA). The fracture surface was observed using a scanning electron microscopy (SEM).

Table 1 Chemical compositions of titanium alloys (mass %).

<table>
<thead>
<tr>
<th>Alloys</th>
<th>B</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>H</th>
<th>Fe</th>
<th>Si</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti–0.5Si–0.2B</td>
<td>0.18</td>
<td>0.01</td>
<td>0.021</td>
<td>0.39</td>
<td>0.0040</td>
<td>0.03</td>
<td>0.52</td>
<td>BAL</td>
</tr>
<tr>
<td>Ti–0.2B</td>
<td>0.21</td>
<td>0.01</td>
<td>0.027</td>
<td>0.38</td>
<td>0.0046</td>
<td>0.02</td>
<td>—</td>
<td>BAL</td>
</tr>
</tbody>
</table>
3. Results and Discussion

3.1 Microstructure and mechanical properties evaluation as a function of reduction

Figure 1 shows optical micrograph of Ti–0.5Si–0.2B cast alloy. Leaf-like alpha phase is observed in the matrix and rod-like dark color particles are distributed in the matrix. Figure 2 reveals the microstructures of cast Ti–0.5Si–0.2B alloy with a higher magnification obtained under back-scattered electron imaging mode by EPMA. Two kinds of particles are observed in the matrix. One is the rod-like in shape with length range of 3–40 μm. The other one is white color and smaller particles with size of 1–2 μm. The results examined by X-ray and EPMA certified that the rod-like particles are TiB intermetallic compound and smaller white particles are Ti₅Si₃ silicide. As the Ti₅Si₃ particles are too fine to be observed in the optical micrograph with lower magnification, it can be deduced that the dark color rod-like particles are TiB compound in the Fig. 1.

The development of microstructure in the Ti–0.5Si–0.2B alloy deformed at 1173 K with reductions of 30%, 50% and 70% are shown in Fig. 3. Samples were sectioned in the three
directions. That is PRD view: rolled surface parallel with rolling direction, LD view: longitudinal surface and TD: Transverse surface vertical to the rolling direction. It can be seen that the microstructure is elongated with increasing the reduction in the LD views, and the variation of the TiB’s amount is not obvious in the PRD views. It means that the possibility that the density of TiB compounds increased with heating times is lower. It should be attributed to the motion and elongation of primary beta grains in the process of rolling deformation.

As the amount of deformation during hot rolling increased, the microstructure of elongated fibrous grains containing fine equiaxed sub-grains are developed. It can be seen that the TiB compounds are elongated to rolling direction and spacing between the TiB fibers decreases with increasing the rolling reduction. As the TiB particles precipitated along the primary beta grains boundary, it is speculated that the grain boundaries are moved and pushed towards each other in the deformation. The TiB compounds deform with grains flowing with good elasticity at high temperature. The fine equiaxed sub-grains are formed by dynamic and static recrystallization during rolling and heating process.

The relationships between reduction and tensile properties of Ti–0.5Si–0.2B, Ti–0.2B alloys are shown in Fig. 4. It can be seen that both of tensile strength and elongation of rolled Ti–0.5Si–0.2B and Ti–0.2B alloys increases with increasing rolling reduction. When the reduction is 50%, the elongation of Ti–0.5Si–0.2B alloy is up to 25% and the tensile strength is about 828 MPa. However, the values of tensile properties are almost kept in the same level when the reduction is from 50% to 70%. Figure 3 shows that the size of sub-grains decreased as the reduction from 30% to 50% but remain approximated constant between 50% and 70%. It means that the mobile grain boundaries eventually pinch off and leave an approximately equiaxed microstructure of sub-grains due to the recrystallization when the rolling reduction is over 50% at 1173 K. Thus, the reduction of 50% could be considered as optimum reduction for the improvement of the microstructure and mechanical properties of Ti–0.5Si–0.2B and Ti–0.2B alloys because the changes of the microstructure and mechanical properties of Ti–0.5Si–0.2B and Ti–0.2B alloys become smaller when the reduction is over 50%. The difference in the strength and elongation for Ti–0.5Si–0.2B and Ti–0.2B alloys could be attributed to the function of Ti$_5$Si$_3$ particles. The TiB particles are in the length range of 5–40 μm. The Ti$_5$Si$_3$ particles are in the size of 0.4–1.5 μm. The fine dispersions Ti$_5$Si$_3$ are expected to inhibit grain boundary mobility and prevent grain growth further, based on Paton et al.’s result. 8)

3.2 Effect of deformation temperature

The effect of the deformation temperature on the microstructural evolution is investigated for the Ti–0.5Si–0.2B alloy deformed to a reduction of 50% at temperature between 573 to 1173 K. The alloy exhibits good thermal plasticity from 773 to 1173 K. However, at 573 K the pressing distance of each rolling should be reduced to 0.25 mm, which is the half of the value that the alloy is rolled at other temperatures. Otherwise, the shear cracks are developed during deformation processing.

The grain structure of the alloy processed at 573 K is fine and elongated as shown in Fig. 5(a). The grain boundaries are relatively straight macroscopically, and the resultant grain

![Fig. 5 Optical microstructures of Ti–0.5Si–0.2B alloy rolled in reduction of 50% in longitudinal direction (LD) at different rolling temperatures.](image-url)
structure is fine needle-like fibrous without equiaxed grains. The size of sub-grains increases with increasing deformation temperature and fine equiaxed grains are evolved in the microstructure at 973 K as shown in Fig. 5(c). Relatively coarser equiaxed sub-grains are formed at 1173 K as shown in Fig. 3(b).

Figure 6 illustrates the variation of tensile ductility and strength of rolled Ti–0.5Si–0.2B alloy in reduction of 50% as a function of deformation temperature. Fracture surfaces of the tensile tested specimens of rolled Ti–0.5Si–0.2B alloy are given in Fig. 7. The elongation increases from 7.5 to 25.7% while the tensile strength decreases from 1036 to 820 MPa when the rolling temperature is from 573 to 1173 K. The improvement in tensile ductility is consistent with the change in the fracture mode. It should be noted that all the fractures are transgranular and ductile but the size of tear ridges becomes smaller with the decrease of deformation temperature. The higher rolling temperature is good for hot-workability, and an increasing deformation temperature results in larger and more equiaxed grain structures and high ductility. On the other hand, the lower rolling temperature results in more refined microstructure and high tensile strength. Thus, it can be seen that the different good combination of strength
and ductility are obtained by reasonable deformation condition. The relatively lower rolling temperature can improve the microstructures and mechanical properties of the titanium alloys more effectively.

4. Conclusions

The cast Ti–0.2B–0.5Si, Ti–0.2B ingots were rolled successfully in this study. The microstructure of elongated fibrous grains containing fine equiaxed sub-grains are formed when the alloy is rolled at 1173 K. Both tensile strength and elongation increased with increasing of reduction. The elongation of Ti–0.5Si–0.2B alloy is up to 25.7% and the tensile strength is about 828 MPa when the alloy is rolled with reduction of 50% at 1173 K. The fine dispersions Ti₅Si₃ are expected to inhibit grain boundary mobility and prevent grain growth further. Reasonable rolling technology and relatively lower rolling temperature can improve the microstructures and mechanical properties of the titanium alloys effectively.

REFERENCES