INTRODUCTION

Friction stir welding (FSW) is an innovative joining technique enabling solid state joining [1]. FSW was initially applied to aluminum and magnesium alloys and the triumph of this technology made it increasingly popular during the last decade. It should be noted, however, that the joining of these low-softening-temperature materials constitute only a small segment of the global welding market, whereas high-softening-temperature materials comprise the dominant part of the welded products. Therefore, there is of commercial interest to expand FSW to the high-softening-temperature materials.

This study is a part of the wide-ranging research project aiming to evaluate the effect of FSW on the microstructure and properties of titanium alloys. In previous papers [2-6], FSW of \( \alpha \) - and \( \alpha + \beta \) titanium alloys was studied. In an attempt to provide a comprehensive overview of the FSW of titanium alloys, the present work is focused on a \( \beta \)-titanium alloy.

EXPERIMENTAL

The material used in the present investigation was a Ti-15V-3Cr-3Al-3Sn metastable \( \beta \)-titanium alloy, the chemical composition (in wt. pct.) of which is shown in Table 1. The material was supplied as 3-mm-thick rolled sheets. The as-received sheets were butt-welded at a tool rotation speed of 400 rpm and a travel speed of 60 mm/min. The welding tool was fabricated from a Mo-based alloy and consisted of a convex shoulder having a diameter of 15 mm and a pin, tapered from 5.1 mm at the shoulder to 3 mm at the pin tip. To minimize surface oxidation, argon shielding was employed around the tool during the welding. Following FSW, the obtained weldments were cross-sectioned perpendicular to the welding direction and studied by using electron backscatter diffraction (EBSD) technique.

Table 1. Chemical composition (wt. pct) of the Ti-15V-3Cr-3Al-3Sn alloy

<table>
<thead>
<tr>
<th>V</th>
<th>Al</th>
<th>Sn</th>
<th>Cr</th>
<th>Fe</th>
<th>C</th>
<th>O</th>
<th>N</th>
<th>H</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.11</td>
<td>3.22</td>
<td>3.05</td>
<td>3.16</td>
<td>0.243</td>
<td>0.005</td>
<td>0.093</td>
<td>0.005</td>
<td>0.011</td>
<td>Balance</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

The transition nature of thermo-mechanical affected zone (TMAZ) in FSW is a key issue to understand how the original grain structure transformed into stir zone (SZ) structure during the welding process. In this study, the microstructure developed on retreating side of the TMAZ was studied in details.

The composite EBSD map obtained from the TMAZ is shown in Fig. 1a and some selected areas are given at higher magnifications in Figs. 1b-d. In the map, low-angle boundaries (LABs) are depicted as thin white lines and high-angle boundaries (HABs) as thick black lines.

Figure 1a demonstrates that the TMAZ extends \(~500\ \mu m\) from the SZ, thus being comparatively narrow. This effect would be associated with the relatively low thermal conductivity of titanium. It is also evident from the figure that crystallographic orientation of the original grains significantly changes in this zone. The muted trend for the geometrical realignment of the parent grains with the SZ/BM border is also worthy of remark.

The high-magnification image in Fig. 1b shows that the original grain boundaries in the TMAZ become essentially wavy and that the developed bulges tend to form small equiaxed grains (arrowed). This indicates an initial stage of the discontinuous recrystallization. On the other hand, the LAB area also significantly increases in the TMAZ, thus showing the extensive formation of the deformation-
induced boundaries. It is also interesting to note that the LABs in the grain interior exhibit substantial sinuosity; however, in a grain scale, their boundary traces lie relatively close to the \{110\} and/or \{112\} slip plane traces (Fig. 1c).

Close to the stir zone (Fig. 1d), some subboundary segments accumulate misorientation over 15° (arrowed), thus transforming into HABs. This observation may be interpreted as an evidence of the continuous recrystallization. Together with the progressive development of the discontinuous recrystallization (encircled in Fig. 1d), this breaks up the original grains into a fine-grained stir zone structure.

**CONCLUSIONS**

The present study examined the grain structure evolution during FSW of Ti-15V-3Cr-3Al-3Sn metastable $\beta$-titanium alloy. The microstructural development was shown to be a complex process involving geometrical effect of strain, continuous and discontinuous recrystallizations.

**REFERENCES**