Annealing Texture and Microstructure Evolution in Titanium during Grain Growth in an External Magnetic Field

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The impact of a magnetic field (17T) on texture and microstructure evolution in cold rolled (75%) commercially pure titanium was investigated. The specifically oriented titanium sheet specimens were heat treated at 1023 K in a magnetic field of 17 T for 60, 120, 180 and 240 minutes. X-ray diffraction and EBSD measurements were utilized to characterize the crystallographic texture and the grain microstructure. The magnetic annealing resulted in an asymmetry of the two major texture components that constantly increased with annealing time. This effect is attributed to a magnetic driving force for grain growth arising from the anisotropic magnetic susceptibility of titanium. Complementary computer simulations of 2D grain growth were employed to analyze the effect of a magnetic field on texture and microstructure evolution. EBSD measurements as well as the computer simulations revealed that a magnetic field affects the grain growth kinetics. Grains with energetically preferred orientations grow faster and their fraction becomes larger than the fraction of more slowly growing grains with disfavored orientations. [doi:10.2320/matertrans.MI200701]

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1. Introduction

The mean grain size as well as the grain growth texture, i.e. the resulting orientation distribution of the grains, determines to a great extent the physical and mechanical properties of polycrystals. Important changes of the grain microstructure and texture of crystalline solids are introduced in the course of recrystallization and grain growth during a heat treatment following plastic deformation.

Grain growth proceeds by the motion of grain boundaries. As was shown theoretically1,2) and proved by experiment3-6) the rate of boundary migration v is proportional to the acting driving force p

\[ v = mp, \]  

(1)

where m is referred to as the grain boundary mobility. Polycrystals are always liable to grain growth owing to a driving force arising from the curvature of the grain boundaries. This driving force is caused by the free energy of the boundary itself since grain boundary motion towards its center of curvature leads to a reduction of grain boundary area. Each boundary segment with the energy γ and the local curvature κ experiences a force per unit area

\[ p_b^k = γκ. \]  

(2)

When a magnetically anisotropic crystalline solid with susceptibility χ << 1 is exposed to a uniform magnetic field an additional magnetic driving force \( p_m^k \) arises owing to the difference of the magnetic energy density \( ω \) in adjacent grains7)

\[ p_m^k = ω_1 - ω_2 = \frac{μ_0 H^2}{2}(χ_1 - χ_2) \]

\[ = \frac{1}{2} μ_0 ΔχH^2(\cos^2θ_1 - \cos^2θ_2), \]  

(3)

where \( μ_0 \) is the magnetic constant, H is the magnetic field strength, \( χ_1 \) and \( χ_2 \) are the magnetic susceptibilities of adjacent grains 1 and 2 along the field direction, Δχ is the difference of the susceptibilities parallel \( χ_p \) and perpendicular \( χ_L \) to the principal (or c) axis of the crystal, \( θ_1 \) and \( θ_2 \) are the angles between the c-axes in both neighboring grains and the magnetic field direction. In contrast to the curvature driving force, the magnetic one does not depend on the boundary properties, i.e. on its energy and shape, but is determined by the magnetic anisotropy of the material (Δχ), the strength of the applied magnetic field and its orientation with respect to the two grains.

An effective magnetic driving force for each grain in a polycrystal can be expressed as the difference between the magnetic free energy density of this grain \( ω \) and an average magnetic free energy density \( ̂ω \) of its neighboring grains that according to eq. (3) can be written as

\[ p_m = ω - ̂ω = \frac{μ_0 H^2}{2} \left( \frac{1}{n} \sum_{j=1}^{n} χ_j \right) \]

\[ = \frac{1}{2} μ_0 ΔχH^2 \left( \cos^2θ - \frac{1}{n} \sum_{j=1}^{n} \cos^2θ_j \right) \]  

(4)

where \( θ \) and \( θ_j \) are the angles between the field direction and principal axes of the considered grain and its n neighboring grains. For instance, if \( Δχ > 0 \) and for the grain and its surrounding the condition \( \cos^2θ \approx 1/n \sum_{j=1}^{n} \cos^2θ_j < 0 \) is completed, the magnetic energy density in this grain is lower than the average energy density of the adjacent grains (\( ω < ̂ω \)) and the magnetic driving force \( p_m < 0 \) favors the growth of this grain. Thus for each grain in the polycrystal depending on particular grain orientation with regard to its nearest neighbors and field direction, the magnetic force can act on its boundaries both with and against the curvature forces.

The orientation dependence of the magnetic driving force provides an opportunity to influence and, therefore, to control development of the grain orientation distribution in a polycrystal, i.e. crystallographic texture during grain growth, by means of magnetic annealing. Experimentally this was
first demonstrated for grain growth in diamagnetic zinc. More recent experiments revealed that texture development in paramagnetic titanium can also be substantially affected by annealing in a high magnetic field.\(^9,10\) In the current study further experimental and computational investigations into the magnetically affected microstructure evolution during grain growth in titanium were conducted.

### 2.2 Texture measurements and grain microstructure characterization

Texture and microstructure were characterized by X-ray diffraction and orientation imaging microscopy (EBSD with HKL Channel 5 software in a FEG-SEM). The orientation distribution functions (ODFs) were determined from a set of six incomplete pole figures \([0002], [1010], [1120], [1011], [1012]\) and [1013] measured with Co \(K_\alpha\) radiation by means of a fully automated texture goniometer in back reflection mode. The ODFs were computed by using the series expansion method with positivity criterion.\(^11,12\) The sample symmetry was regarded triclinic to account for asymmetric textures after annealing in the magnetic field. Details concerning the sample preparation for macrotexture measurements are given elsewhere.\(^9\) The samples for EBSD measurements were additionally electrolytically polished in a solution of 300 ml CH\(_3\)OH, 180 ml C\(_6\)H\(_5\)O\(_2\) and 1 ml Vogel-Sparbeize (proprietary product of Buehler company).

### 2.3 2D modeling of grain growth

We employed complementary computer simulations of 2D grain growth to analyze the effect of a magnetic field on texture and microstructure evolution in titanium. The simulation algorithm is based on vertex and front-tracking models which are most appropriate for curvature driven grain growth.\(^13-16\) The grain structure in this algorithm is represented by differently oriented grains, separated by boundaries that intersect at triple junctions (real vertices). The grain boundaries in turn consist of points (virtual vertices) along the boundary length according to the boundary curvature.\(^17\) During grain growth without an external field all virtual vertices move under the local curvature driving force \(p = p_c = \gamma \cdot k\) perpendicular to the boundary. In the presence of a magnetic field the kinetic equation of boundary motion \(v = m \cdot p\) is solved for all virtual vertices with a driving force \(p = p_c + p_m\), where \(p_m\) is calculated according to eq. (3).\(^17\)

Figure 2 depicts the simulated grain size evolution of a 2D polycrystal at zero field, i.e. under a pure curvature driving force. Figure 2(a) shows the computed time dependence of the normalized mean grain area. The mean grain area is seen to increase linearly with annealing time (Fig. 2(a)).
behavior is characteristic for curvature driven normal grain growth in homogeneous systems (constant grain boundary energy and mobility). Furthermore, it was assessed whether the model reproduces the topological microstructure evolution according to the von Neumann-Mullins relation, which connects the rate of grain area change $\frac{dS}{dt}$ to the topological class $n$ of a grain (Fig. 2(b)). The agreement between the classical relation
\[
\frac{dS}{dt} = \frac{\gamma m_0 \cdot \pi}{3} (n - 6) \approx 1.047 m_0 \gamma (n - 6) \tag{5}
\]
and the linear fit of the simulated results $dS/dt = 1.044 m_0 \gamma (n - 6.0029)$ is excellent. The results convincingly demonstrate the capability of the used simulation model to study grain growth in homogeneous 2D systems.

3. Magnetically Affected Texture and Grain Structure Evolution

3.1 Texture evolution during grain growth in magnetic field

The cold-rolling texture with two symmetrical peaks in the (0002) pole figure (Fig. 3) measured after 75% reduction is very similar to those already reported in literature for low alloyed titanium. As seen in the $\varphi_1 = 0^\circ$ and $\varphi_1 = 180^\circ$ ODF sections (Figs. 3(b), (c)), two major ODF peaks are widely spread around the orientations $(\varphi_1, \Phi, \varphi_2) = \{(0,35,0)\}$ and $(180,35,0)$ in Euler space.

The grain growth texture after 15 min and subsequent 60 min annealing at $750^\circ$ is characterized by the highest ODF density at $(0,35,30)$ and $(180,35,30)$ (Fig. 4). The ODF sections $\varphi_1 = 0^\circ$ and $\varphi_1 = 180^\circ$ depict, however, that the ODF density remains high in the entire angular range of $\varphi_2$. It is worth noting that a similar texture was also measured for specimens annealed at 1023 K for 15 min at zero field plus 60 min in a magnetic field of 17 T (bottom).

The application of a magnetic field of 17 T after 15 min conventional annealing dramatically affects the texture evolution during grain growth. As also observed in our previous experiments, the peaks in the (0002) pole figures do not remain symmetrical anymore. After magnetic annealing for 60 min the ODF intensity at $(180,35,30)$ exceeds the corresponding intensity after annealing at zero field by a factor of 1.34, whereas the intensity at $(0,35,30)$ decreases to about 65% of the zero field intensity. The texture asymmetry continuously increases with annealing time. After magnetic annealing for 240 min the intensity ratio of both major ODF peaks amounts to 3.5 (Fig. 7). However, since a magnetic field affects the intensity of all orientations with $\varphi_1 = 0^\circ / 180^\circ$ and $\Phi = 35^\circ$ in the entire interval of $\varphi_2$, a more appropriate way to reveal the magnetically induced texture anisotropy and its increase with annealing time is to compare the (0002) pole density of both major peaks centered around $(0,35,\varphi_2)$ and $(180,35,\varphi_2)$ (Fig. 8).

The development of an asymmetrical texture during magnetic annealing is obviously caused by the additional magnetic driving force during grain growth. During magnetic annealing the specimens were oriented in such a manner that the c-axes of the grains which compose a texture peak around the orientations $(180,35,\varphi_2)$ were aligned perpendicular to the field direction. With the difference in magnetic susceptibility parallel and perpendicular to the c-axis $\Delta \chi > 0$ for
titanium, the magnetic free energy density of these grains attains a minimum that results in an additional driving force for their growth ($p_m < 0$).

As seen in Fig. 8, an increase of the $(180, 35, \varphi_2)$ peak intensity during magnetic annealing corresponds to a decrease of the intensity of the $(0, 35, \varphi_2)$ peak. This means that on average grains close to the energetically favorable orientations $(180, 35, \varphi_2)$ ($p_m < 0$) grow at the expense of grains close to $(0, 35, \varphi_2)$, whose free energy is increased in a magnetic field by the amount $p_m > 0$ (eq. (3)). Accordingly, grains with the $(180, 35, \varphi_2)$ orientations can be expected to grow significantly larger than grains comprising the other peak.

Figure 9 shows the texture development in a 2D-polycrystal as obtained by computer simulations of 2D grain growth. These simulations made use of the actual experimental conditions. The initial microstructure and texture was reconstructed from individual orientation data (EBSD mapping) measured on a Ti specimen annealed for 15 min at 1023 K (Table 1). Grain boundary energy and mobility were assumed to be uniform. The magnetic energy density was computed for each grain and the condition that the magnetic field was applied perpendicular to the rolling direction of the specimen and inclined 32° from the transverse direction, as indicated by a cross in the pole figure in Fig. 9(c). Therefore, depending on their surroundings, grains close to $(180^\circ, 35^\circ, \varphi_2)$ will experience an additional force to grow ($p_m < 0$), since their c-axes are aligned nearly normal to the field direction and thus, contain the smallest magnetic energy density.

The results of simulations quantitatively agree with experimental observations. After annealing at zero field the simulated texture remains symmetrical (Fig. 9(b)), whereas after magnetic annealing the $(180, 35, \varphi_2)$ texture peak with

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**Fig. 6** (a) $(0002)$ pole figures and ODF sections at (b) $\varphi_1 = 180^\circ$ and (c) $\varphi_1 = 0^\circ$ for specimens annealed at 1023 K for 195 min (top) and for 15 min at zero field plus 180 min in a magnetic field of 17 T (bottom).

**Fig. 7** (a) $(0002)$ pole figures and ODF sections at (b) $\varphi_1 = 180^\circ$ and (c) $\varphi_1 = 0^\circ$ for specimens annealed at 1023 K for 15 min at zero field and 240 min in a magnetic field of 17 T.

**Fig. 8** $(0002)$ pole density along TD (Figs. 5–8) for 75%-rolled Ti sheet samples after annealing at 1023 K (a) for 75 min without field; (b) for 15 min at zero field and 60 min, (c) 120 min, (d) 180 min, (e) 240 min in a magnetic field of 17 T.
orientations. First, the magnetic field was applied parallel to
simulations were performed for two different specimen
texture was caused exclusively by the magnetic field, the
normally distributed grain size. To prove that the produced
Voronoi tessellation and consisted of 20000 grains with
structure for these simulations was generated by means of
orientation distribution (Fig. 10(a)). The initial grain micro-
was applied to a 2D polycrystal with initially random
orientations in a polycrystal during grain growth is perfectly
captured by computer simulations, where a magnetic field
ability of a magnetic field to produce preferred
an additional orientation magnetic driving force.
tiate that the texture evolution during grain growth in a
magnetic field of magnetically anisotropic titanium is due to
an additional orientation dependent magnetic driving force.

3.2 Grain microstructure development during grain
growth in a magnetic field
The magnitude of the texture peaks obtained by X-ray
diffraction is determined by the total area of grains having a
respective orientation. Macrotexture measurements therefore
do not render information on the grain microstructure with
respect to grain size and number of grains making up
different texture components. This information can, however,
be obtained by orientation imaging with EBSD. Since the

c-axes perpendicular to the field becomes much stronger than the
other peak (Fig. 9(c)).

The ability of a magnetic field to produce preferred
orientations in a polycrystal during grain growth is perfectly
captured by computer simulations, where a magnetic field
was applied to a 2D polycrystal with initially random
orientation distribution (Fig. 10(a)). The initial grain micro-
structure for these simulations was generated by means of
Voronoi tessellation and consisted of 20000 grains with
normally distributed grain size. To prove that the produced
texture was caused exclusively by the magnetic field, the
simulations were performed for two different specimen
orientations. First, the magnetic field was applied parallel to
the sheet normal (ND). In this case grains with c-axis parallel
to the (\(\varphi_1, 90, \varphi_2\)) orientations (i.e. with c-axes perpendicular
to ND) possess a minimum magnetic free energy and therefore experience an additional driving force for their
growth (\(p_m < 0\)). This results in a texture with maximum
(0002) pole intensity at (\(\varphi_1, 90, \varphi_2\)) and minimum at (\(\varphi_1, 0, \varphi_2\))
(Fig. 10(b)). Second, a magnetic field was directed parallel to
the rolling direction (RD). Correspondingly, a maximum
magnetic energy was generated in grains with the c-axis
aligned along (90, 90, \(\varphi_2\)) (i.e. RD), and the magnetic driving
force promoted their shrinkage (\(p_m > 0\)), whereas in grains with
the c-axis perpendicular to RD (i.e. aligned along (0/
180, \(\Phi, \varphi_2\)) this force favored their expansion (\(p_m < 0\)). As a
consequence, a texture with a maximum intensity at (0/
180, \(\Phi, \varphi_2\)) developed (Fig. 10(c)). The simulations substanti-
tate that the texture evolution during grain growth in a
magnetic field of magnetically anisotropic titanium is due to
an additional orientation dependent magnetic driving force.

<table>
<thead>
<tr>
<th>Time</th>
<th>Field</th>
<th>Total number of grains</th>
<th>Subset</th>
<th>Mean grain size, (\mu m)</th>
<th>Number of grains</th>
<th>Grain fraction</th>
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<td>8648</td>
<td>both (0, 35, \varphi_1) (180, 35, \varphi_1)</td>
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<td>8207</td>
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<td></td>
<td></td>
<td></td>
<td>(\varphi_2)</td>
<td>39</td>
<td>4321</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(180, \varphi_2)</td>
<td>40</td>
<td>3981</td>
<td>0.46</td>
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<tr>
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<td>0T</td>
<td>6532</td>
<td>both (0, 35, \varphi_1) (180, 35, \varphi_1)</td>
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<td>6371</td>
<td>0.98</td>
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<tr>
<td>60 min</td>
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<td></td>
<td>(\varphi_2)</td>
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<td>3276</td>
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<td></td>
<td></td>
<td></td>
<td>(180, \varphi_2)</td>
<td>83</td>
<td>3095</td>
<td>0.48</td>
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<td>5919</td>
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<td>5619</td>
<td>0.98</td>
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<tr>
<td>120 min</td>
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<td>2598</td>
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<td></td>
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<td>(180, \varphi_2)</td>
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<td>3021</td>
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<tr>
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<td>4407</td>
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<td>2328</td>
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<td></td>
<td>(180, \varphi_2)</td>
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<td>1940</td>
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<td>102</td>
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<td></td>
<td></td>
<td></td>
<td>(\varphi_2)</td>
<td>116</td>
<td>992</td>
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<td></td>
<td></td>
<td></td>
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<td>135</td>
<td>1455</td>
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<td>0.98</td>
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<tr>
<td>240 min</td>
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<td></td>
<td>(\varphi_2)</td>
<td>126</td>
<td>593</td>
<td>0.24</td>
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<td></td>
<td></td>
<td>(180, \varphi_2)</td>
<td>152</td>
<td>1257</td>
<td>0.74</td>
</tr>
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</table>
observed textures in the current experiments were characterized by a high ODF density at the (0/180,35,ψ2), it is reasonable to subdivide the whole set of grains into two subsets with orientations around (0,35,ψ2) and (180,35,ψ2). These two subsets represent the two texture peaks in the (0002) pole figures in Figs. 4–8. For an assignment of the grains to one of the two subsets a cut-off radius of 35° per subset was applied. An overlapping of subsets was avoided by the restrictive condition that each orientation can belong to only one, the nearest, subset. The result is given in Table 1 and Fig. 11. Since the observed texture is rather sharp a threshold grain misorientation of 3° was used to delimitate different grains.

The results reveal that the overall growth kinetics of all grains (Fig. 12), are enhanced by a magnetic field. In the entire investigated annealing time interval the mean grain size after magnetic annealing was found to be slightly but distinctly larger than after annealing at zero field. In both cases the growth kinetics follows a relation \( d \propto k t^n \), where \( d \) and \( t \) denote the mean grain size and the annealing time, respectively. The magnitude of the exponent \( n \) for magnetic annealing at 17T, \( n_{17T} = 0.39 \), was obtained by a linear fit of the diagram in Fig. 12 and was found to be slightly higher than the exponent \( n_{0T} = 0.37 \) for zero field annealing. As seen in Table 1, there is no difference in the growth kinetics for grains in different grain subsets in specimens annealed without field. By contrast, as expected from results of macrotexture measurements (Fig. 8), in specimens annealed in a magnetic field the mean size of grains in the subset (180,35,ψ2) was larger than in the subset (0,35,ψ2). Figure 12(b) illustrates that the growth kinetics in the grain subset (180,35,ψ2) are faster (\( n_{17T} = 0.44 \)) than the average kinetics of all grains, whereas growth is retarded for grains in the subset (0,35,ψ2) (\( n_{0T} = 0.32 \)).

A qualitatively very similar behaviour, i.e. that a magnetic field slows down or increase the growth rate of differently oriented grains, is also obtained by a computer simulation of magnetically affected grain growth in a 2D polycrystal (Fig. 13).

However, the observed texture anisotropy after magnetic annealing can not be completely justified by this relatively slight difference in the mean size of grains in different grain subsets. For instance, the ratio of the mean grain area in both subsets after 240 min magnetic annealing is \( d^{2}_{(180,35,\phi_{2})} / d^{2}_{(0,35,\phi_{2})} = 1.45 \), whereas the ratio of the pole intensity for both texture components in Fig. 8(e) amounts to 4.3. As given in Table 1 and illustrated in Fig. 14, a magnetic annealing also results in a substantial change of the number of grains in both grain subsets. The two major texture peaks in the (0002) pole figures after annealings without field are not completely symmetric (Figs. 4–6) which is reflected by the non-equal number of grains in the respective subsets: the non-equal number of grains in the respective subsets: the non-equal number of grains in the respective subsets: the non-equal number of grains in the respective subsets: the non-equal number of grains in the respective subsets: the non-equal number of grains in the respective subsets: the non-equal number of grains in the respective subsets: the non-equal number of grains in the respective subsets: the non-equal number of grains in the respective subsets.
annealing the grains in the energetically favored subset (180,35,φ2) substantially outnumber the grains in the disfavored subset (0,35,φ2) (Fig. 14).

The same behaviour is also captured by computer simulations. As shown in Fig. 15(a)–(b), the fraction of the energetically favored grain subset (180,35,φ2) (p_m < 0) increases during the annealing in the field, whereas the fraction of the (0,35,φ2) grain subset decreases. If a magnetic field is applied parallel to the sheet normal (ND) (see Fig. 10) and therefore grains with Φ = 90° have the minimum magnetic free energy, similar results are obtained for the change of grain fractions in (φ1,90,φ2) and (all other grains) subsets (Fig. 15(c)–(d)).

Therefore, the analysis of individual orientation measurements and the results of computer simulations reveal that a magnetic field affects the grain growth kinetics in such a way that the growth of grains with energetically favored orientations is enhanced, whereas the growth of grains with disfavored orientations is retarded. Moreover, grains with energetically preferred orientations do not only grow faster, but their number fraction is larger than half of all grains and continuously rises during magnetic annealing, while the fraction of grains with disfavored orientations decreases. It is worth noting that this result provides a possible explanation for the magnetic enhancement of the growth kinetics averaged over all grains: the faster growth rate in a larger and constantly rising grain fraction necessarily results in an increased average growth rate.

The observed difference in the number of grains comprising both texture peaks in the (0002) pole figures after magnetic annealing (Figs. 4–7) can be attributed to magnetically shifted grain growth kinetics. As shown in our previous study, the Hillert relation for the growth rate of grains with size R in the presence of a magnetic field can be extended to

\[
\frac{dR}{dt} = cm_b\gamma\left(\frac{1}{R} - \frac{1}{R_m}\right) - m_b p_m
\]

where γ and m_b are the grain boundary energy and mobility (equal for all grain boundaries), and α is a dimensionless constant. In contrast to the classical Hillert approach, the mean grain size R is not the critical size of grains which neither grow nor shrink anymore. If grain growth occurs in a magnetic field, the threshold grain size R_{th} can be expressed as

\[
R_{th} = \frac{\tilde{R}}{1 - \frac{R_{p_m}}{\alpha\gamma}}
\]

Due their “high energy” orientations, grains comprising the (0,35,φ2) texture peak on average experience a positive magnetic driving force, p_m > 0, while for “low energy” grains of the (180,35,φ2) peak a magnetic driving force is negative, p_m < 0. Therefore, according to eq. (7), the threshold grain size for shrinkage or growth of high energy grains increases, whereas it decreases for low energy grains. Correspondingly, more high energy grains shrink and disappear and, on the other hand, more low energy grains grow than it would be the case at zero field. Obviously this should result in an increase or decrease of the number fractions of the differently oriented grains as observed in the current experiment and simulations.
The results of simulations also revealed that the magnetically affected grain growth kinetics is consequentially reflected in the behaviour of the grain size distribution for differently oriented grains. Figure 16 depicts these distributions for energetically favored and disfavored grains before and after the magnetic annealing. The magnetic annealing is seen to result in a distinct shift of grain size distributions to smaller and larger grain sizes for high and low energy grains, respectively.

An application of a magnetic field during annealing results not only in the change of the growth rate of differently oriented grains, but substantially alters the final distribution of the grains of different topological classes (Fig. 17). As seen in Fig. 18, in the presence of a magnetic field the computed dependence of the rate of the grain area change $dS/dt$ on the topological class $n$ of the grain does not intersect the n-axis at $n = 6$ (see Fig. 2). Rather this dependence moves in opposite directions for grains with energetically favored and disfavored orientations. In Ref. 23, where the von Neumann-Mullins approach was extended to account the influence of a magnetic field, was shown that the topological class of the stable grains can be expressed as

$$n_n = 6 \left(1 + \frac{R_{nh} p_m}{\gamma} \right)$$  \hspace{1cm} (8)

According to eq. (8), the topological class of the stable grains in preferred energetic configurations ($p_m < 0$), is reduced to $n_n < 6$ and raised to $n_n > 6$ for grains in unfavored configurations ($p_m > 0$). This practically means that grains with topological class 6 do not remain stable anymore in the magnetic field, but either grow or shrink, that results in a significant decrease of the fraction of grains with $n = 6$ in a 2D-polycrystal after magnetic annealing (Fig. 17(b)).

Obviously, a magnetic field in the current experiment and simulations could facilitate the observed changes in the orientation distribution of grains and growth kinetics of differently oriented grains since the magnitude of the generated magnetic driving force during grain growth was comparable to curvature forces. Indeed, for normal (continuous) grain growth eq. (2) can be re-written as

$$p_c = \frac{2\gamma}{r},$$  \hspace{1cm} (9)

where $r$ is the radius of curvature, which usually scales with the grain size but exceeds it by about an order of magnitude. For a mean grain size of about 40\,$\mu$m that corresponds to the grain structure in the investigated titanium before the application of a magnetic field (see Table 1), the curvature force amounts to about 2\,kJ/m$^2$ and then decreases with a rising mean grain size during the annealing. In contrast, according to eq. (3) the maximum magnetic driving force in the current experiment ($H = 1.18 \times 10^5$\,A/m, c-axes of grains oriented close to (180,35,92) are almost normal to the field direction) remains constant during annealing. It is equal to the difference of the magnetic energy density between grains with ideal orientations (0,35,92) and (180,35,92) and amounts to about $p_m = 1.5\,kJ/m^3$.

Apparently, for fine-grained structures the magnetic driving force generated by a magnetic field of the same strength is much smaller than the curvature force and, therefore, is unlikely to cause measurable texture anisotropy during the annealing. It is worth noting, however, that the impact of a magnetic field on grain growth is not only confined to a change of the net driving force for grain boundary motion. As was observed recently in experiments with 78%-cold rolled titanium,\textsuperscript{25} grain growth at its early stage during annealing at 803\,K (mean grain sizes in the range between 2 and 3\,\mu$m) was found to be distinctly enhanced by a magnetic field of 19T that was attributed to the magnetically accelerated grain boundary mobility.\textsuperscript{25}

4. Summary

The effect of a magnetic field on texture and grain microstructure evolution during grain growth in titanium was addressed. Annealing of 75% rolled titanium sheet specimens...
in a specific inclined configuration at 1023 K in a magnetic field of 17 T for 60, 120, 180 and 240 minutes results in an increasing asymmetry of the usually symmetrical texture. The intensity of the texture peak composed by orientations close to \((180, 35, \varphi_2)\) rises, while the intensity of the \((0, 35, \varphi_2)\) peaks decreases. Obviously, this behaviour is due to the additional driving force for grain growth arising in a magnetic field and caused by the anisotropy of the magnetic susceptibility of paramagnetic titanium. The remarkable property of a magnetic field to produce preferred orientations in a magnetically anisotropic material was further analyzed by computer simulations of 2D grain growth.

EBSD measurements as well as simulations revealed that the grain growth kinetics in titanium become orientation dependent in a magnetic field. The growth of grains with energetically favored orientations is enhanced, whereas the growth of grains with disfavored orientations is retarded. However, grains with energetically preferred orientations not only grow faster, but their fraction is larger than a half of the total grains number and continuously rises during magnetic annealing, while the fraction of slower growing grains with disfavored orientations decreases. Furthermore, as shown by computer simulations, the application of a magnetic field during annealing results not only in the change of the growth rate of differently oriented grains, but distinctly alters the final distribution of the grains of different topological classes.

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