

# Quantifying Crystallographic Texture Variation in a Titanium Billet

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**Abstract.** Ti-834 and other titanium alloy forgings can contain regions of similarly orientated primary alpha grains called macrozones that can have a deleterious effect on performance in-service. Understanding the origin of macrozones and how they change during processing is an important step in optimising process routes for these alloys. In this work a detailed characterisation of crystallographic texture variation was carried out on the cross-section of a 250 mm diameter Ti-834 billet using optical metallography, EBSD and neutron texture analysis. Results showed there was a variation in texture and macrozone size and shape through the billet with each macrozone composed of a single hcp component, with varying degrees of orientation spread. The texture of the majority of macrozones can be classed as either axial (c-axis parallel to the billet axis) or transverse (c-axis perpendicular to the billet axis). In the centre of the billet cross-section, the global texture was dominated by a fibre-like  $\{10\bar{1}0\}$  texture due to a dominance of transverse macrozones. At the edge, there was a greater proportion of axial macrozones which gave rise to an additional  $\{0002\}$  component.

## 1. Introduction

This paper reports on work that was carried out to investigate and characterise microstructure, microtexture and global textures in a billet of the titanium alloy Ti-834 (Ti–5.8Al–4Sn–3.5Zr–0.7Nb–0.5Mo–0.35Si–0.06C in wt%). Several titanium alloys, including Ti-834, Ti6Al4V and Ti6242, etc., in multiple product forms have been reported to contain regions with strong local textures referred to as macrozones (e.g., [1, 2, 3]). The main focus of this work was to study the effect of location on the macrozones in terms of their size, shape, texture intensity and crystallographic orientation. This was accomplished using a combination of optical microscopy, EBSD and neutron texture analysis to study a cross-sectional slice from the billet.

## 2. Experimental Procedure

An 8 mm thick transverse slice was obtained from a 250 mm diameter billet of Ti-834. The billet was sectioned for analysis using optical microscopy, neutron texture analysis and EBSD utilising a range of step sizes. The locations analysed are indicated in Figure 1. Specimens labelled 1-7, with dimensions 15 x 10 x 3 mm, were examined using EBSD. Specimens labelled A-Q, with dimensions 15 x 15 x 8 mm, were used for the neutron texture analysis. The macroscopic coordinate system used for this analysis is



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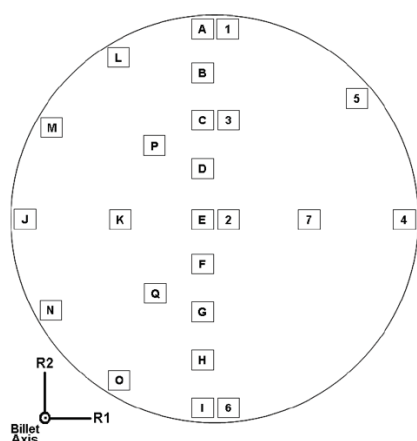
also shown in Figure 1. It should be noted that the two perpendicular radial directions (R1 and R2) were arbitrarily chosen and are not related to specific forging directions, since these were not known.

A detailed description of the experimental setup for the EBSD and neutron texture analysis can be found in Davies et al. [4].

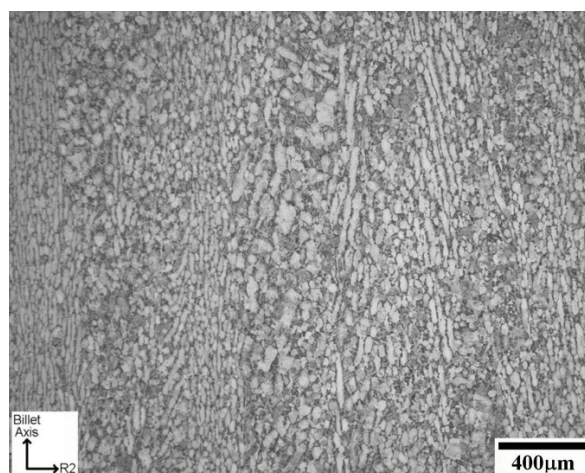
### 3. Results

#### 3.1. Characterisation at the Scale of the Macrozones

Optical microscopy (Figure 2) at lower magnification showed that the billet contained regions of developed yet aligned primary  $\alpha$ p grains.



**Figure 1.** Specimen positions and macroscopic coordinates for the billet texture characterisation.



**Figure 2.** Longitudinal section showing columnar shaped groupings of aligned  $\alpha$ p grains. Both the groupings and the  $\alpha$ p grains themselves are predominantly aligned with the billet axis.

To provide information on the crystallographic orientation of the aligned regions, an EBSD map was acquired from the centre of the billet in the longitudinal plane using a step size of  $3\mu\text{m}$ . The map is displayed in Figure 3a using Euler colouring and Figure 3b using inverse pole figure (IPF) colouring (note that the IPF colouring is with respect to the billet axis instead of the map normal, which means that the colours show which crystallographic planes of the  $\alpha$  phase lie in the transverse plane of the billet). It can be seen that the regions of aligned grains also share common crystallographic orientations. This demonstrates that regions of aligned  $\alpha$ p grains are in fact macrozones, regions with strong local textures. In the longitudinal section, the macrozones have thicknesses ranging from approximately 100 to  $1000\mu\text{m}$  and are up to several thousand microns in length.

To provide more detailed information on the crystallographic orientations of the  $\alpha$  phase in the aligned regions, two EBSD maps were acquired from specimen 2 (centre) and 1 (edge) using a step size of  $3\mu\text{m}$ . These maps were acquired in the transverse plane in order to maximise the number of aligned regions contained in the maps. The map from the centre of the billet (specimen 2) is shown in Figure 3c using a combination of band contrast and IPF colouring to reveal microstructure as well as orientation information. It can be seen that viewed in the transverse plane, the macrozones are much more equiaxed. The macrozones in the map from the centre of the billet are mainly blue or red in colour. In the blue macrozones, the prismatic  $\{10\bar{1}0\}$  planes lie in the transverse plane of the billet, which means that the c-axis must also lie in the transverse plane in a direction perpendicular to the billet axis. We can therefore describe these macrozones in terms of the c-axis direction, as transverse type. In the red macrozones, the  $\{0002\}$  planes lie in the transverse plane, which means the c-axis is aligned with the billet axis. In terms of the c-axis direction, these macrozones can be described as axial type. More

diffuse groups of green grains are also present. These are also transverse type but in this case, the  $\{11\bar{2}0\}$  planes lie in the transverse plane. The basal transverse macrozones tend to be larger and occupy a greater portion of the scanned region compared to the basal axial macrozones. Figure 4 shows a typical example of a basal transverse macrozone in greater detail, together with a misorientation map and pole figure of the measured orientations in the selected macrozone. It can be seen from the figure that almost every  $\alpha$  grain in the macrozone has a similar crystallographic orientation, which results in an extremely strong local texture. For the basal transverse macrozones, there was a very strong tendency for the c-axis of the crystal to be in the same direction as the direction of grain alignment in the transverse plane. The misorientation map shows misorientations between adjacent  $\alpha$  grains because of the thin layers of  $\beta$  phase between the  $\alpha$  grains was not indexed. The clear lack of boundaries within the basal transverse macrozone shows that most of the grains within the macrozone are misorientated from their neighbours by less than  $15^\circ$ . Figure 5 shows a typical example of a basal axial macrozone in greater detail. It can be seen from the pole figure that there is a larger spread in the grain orientations compared to the basal transverse macrozone, which results in a weaker local texture. The misorientation map shows that most of the grains within a basal axial macrozone are misorientated from their neighbours by more than  $15^\circ$ .

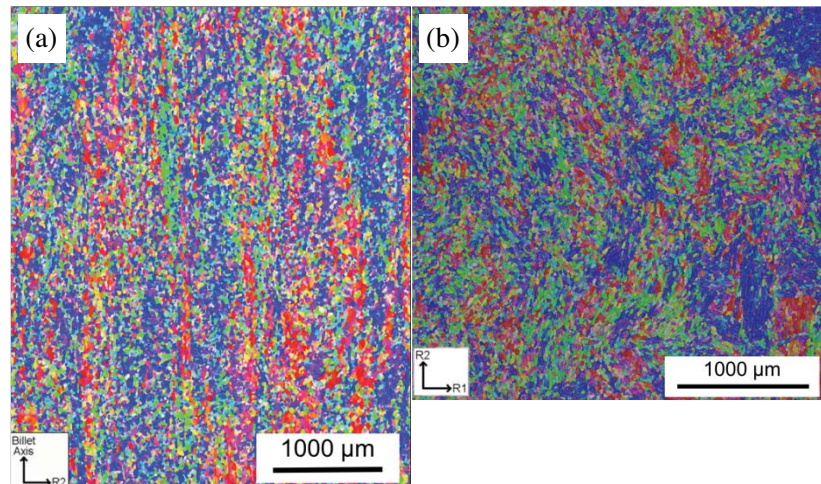
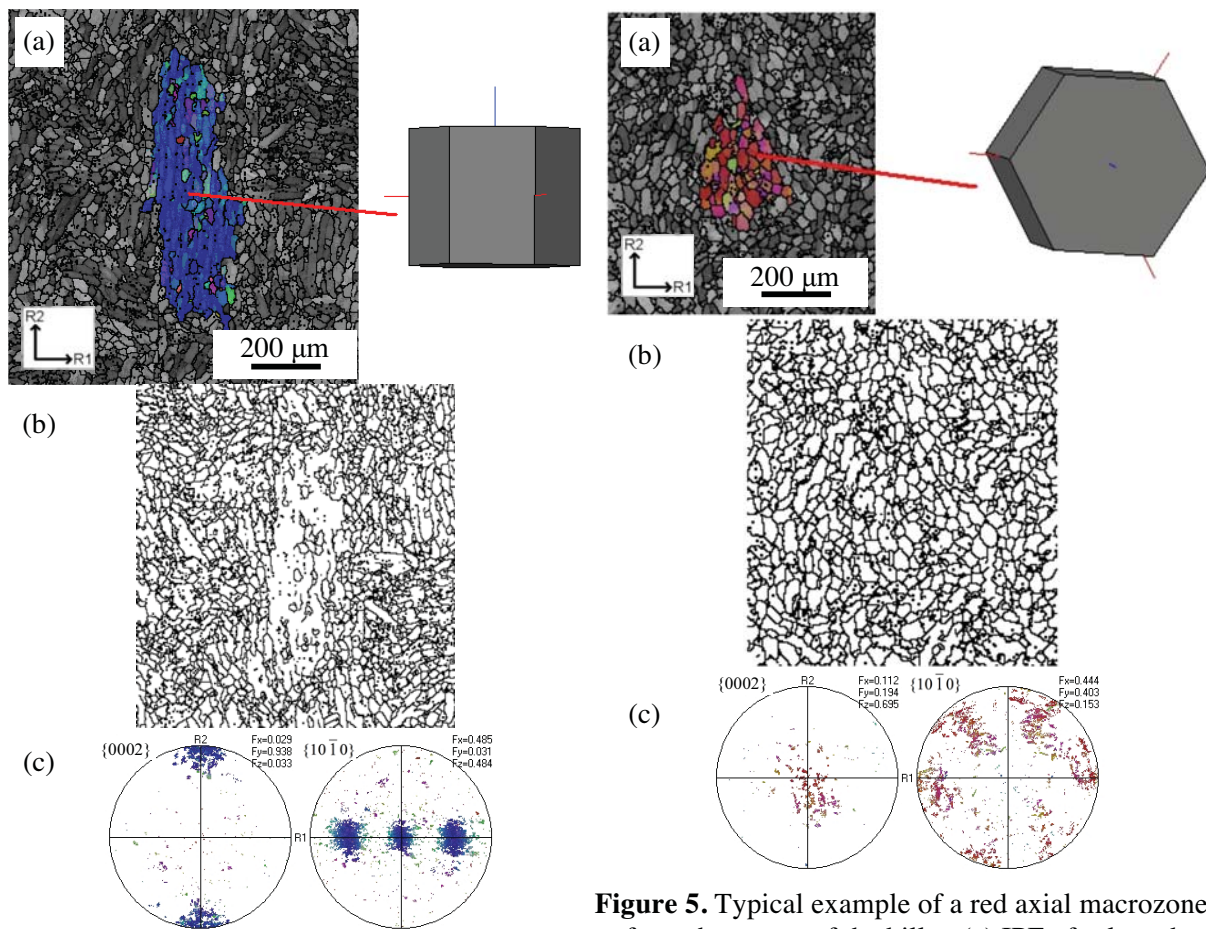


Figure 3. (a) EBSD IPF colouring map of the  $\alpha$  phase in a longitudinal section from the centre of the billet (specimen 2). (b) IPF colouring + band contrast map of the  $\alpha$  phase in a transverse section from the centre of the billet (specimen 2).

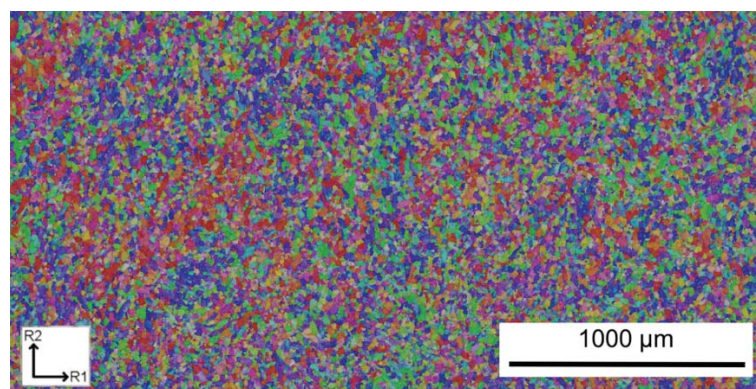
The map from the edge of the billet (specimen 1) is shown in Figure 6. Unlike the centre of the billet, the grains are more or less equiaxed in the transverse plane, so there is no clear alignment of the grain structure in the map. However, macrozones can once again be identified as areas with a dominant IPF colour. Compared to the centre of the billet, macrozones at the edge appear to be more diffuse, which is at least partly due to a higher volume fraction of secondary  $\alpha$ s at the edge. This  $\alpha$ s will be expected to have a spread of orientations due to the  $\beta \rightarrow \alpha$  transformation even if there is a strong variant selection. The largest macrozones are of the basal axial type. Smaller groupings of grains with basal transverse type orientations with both  $\{10\bar{1}0\}$  or  $\{11\bar{2}0\}$  parallel are also present. Detailed examination of both the blue and red macrozones showed that their strengths are similar but neither are as strong as the blue transverse macrozones that featured prominently in the centre of the billet. The boundary maps for the macrozones at the edge also showed that most of the  $\alpha$  grains in the macrozones are misorientated from their neighbour grains by more than  $15^\circ$ .





**Figure 5.** Typical example of a red axial macrozone from the centre of the billet. (a) IPF of selected macrozone, (b) 15° misorientations, (c) pole figures

**Figure 4.** Typical example of a blue transverse macrozone from the centre of the billet. (a) IPF of selected macrozone, (b) 15° misorientations, (c) pole figures



**Figure 6.** EBSD map of the  $\alpha$  phase in a transverse section (perpendicular to billet axis) from the edge of the billet (specimen 1). IPF colouring + band contrast.

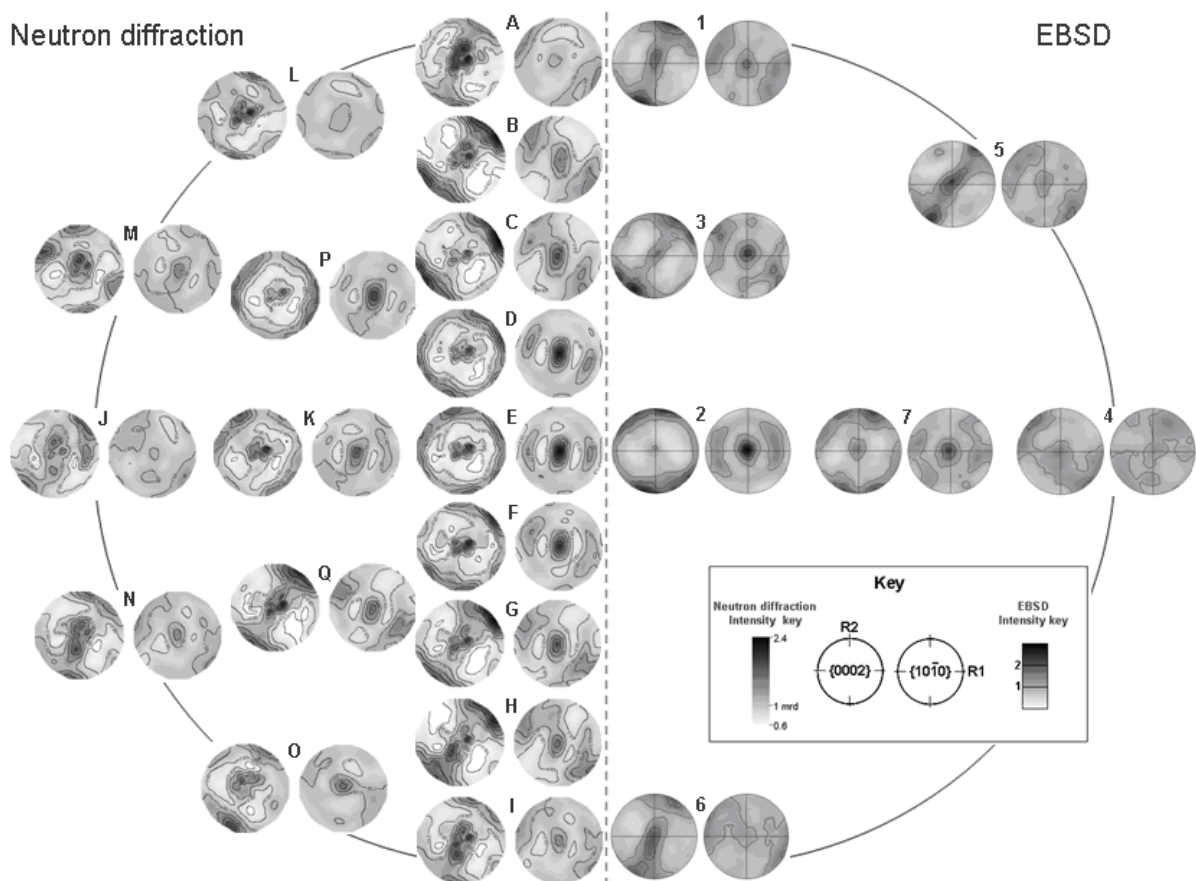
### 3.2. Characterisation of Global Textures and Macrostructural Alignment

The results of the neutron and EBSD texture analysis are presented together in Figure 7, in which each texture measurement is superimposed on the billet slice according to its location. Each texture measurement is represented by an {0002} and a {10-10} pole figure contour plot in equal area

projection. Orientation image maps for the EBSD analysis on specimens 1 to 7 are displayed in Figure 8. IPF colouring is used with respect to the billet axis, which means that the colours show which crystallographic planes of the  $\alpha$  phase lie in the transverse plane of the billet.

A direct comparison can be made between the EBSD and neutron texture analysis techniques by comparing the textures of specimens taken from adjacent regions in the billet cross-section i.e. 1 with A, 3 with C, 2 with E, and 6 with I. It can be seen that there is reasonably good agreement between the EBSD and neutron texture measurements, apart from relatively small differences in the intensity of some of the poles. The close agreement suggests that the neutron texture analysis has successfully reproduced the global textures, and also indicates that the areas analysed using EBSD were large enough for representative global textures to be acquired.

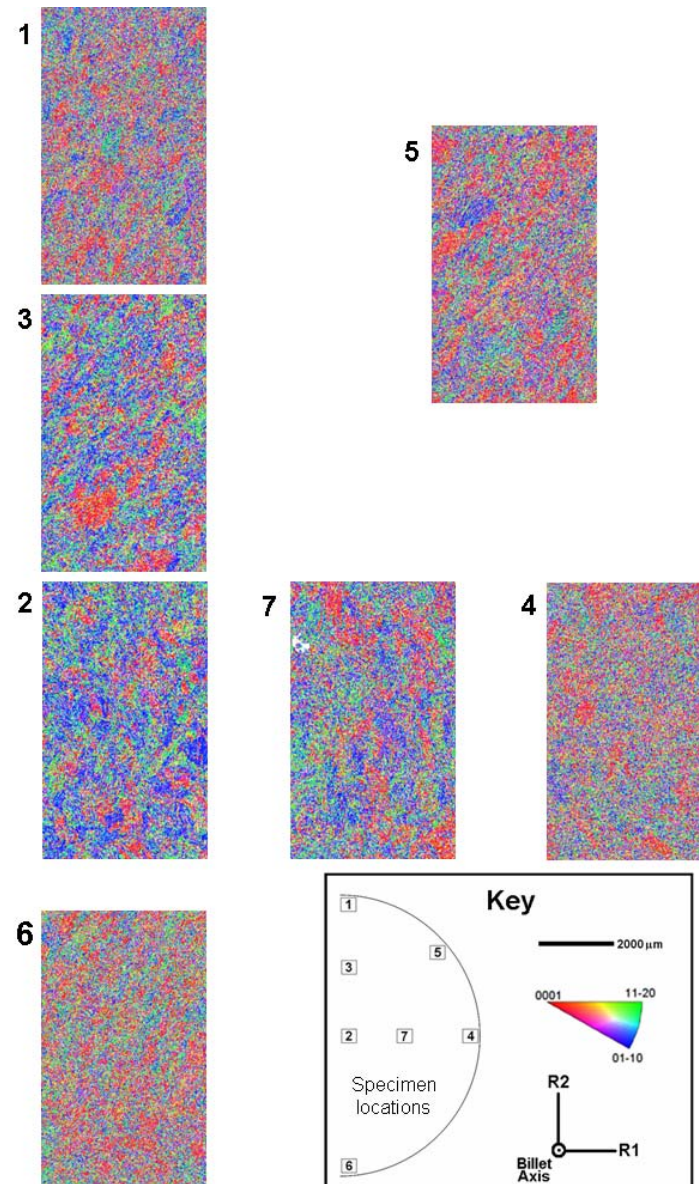
In general, the global billet textures were found to be quite weak, with maximum multiples of random distribution (m.r.d.) values of between 2 and 3. However, there are clearly global textures present, which indicates that the macrozones tend to have preferred orientations. Furthermore, these textures change depending on the location in the billet.



**Figure 7.** Billet texture results. Specimens A-Q analysed by neutron diffraction, specimens 1-7 analysed by EBSD.

When the texture results (Figure 7) are viewed in conjunction with the EBSD maps (Figure 8), the most obvious trend is a centre to edge variation in the relative amounts of the transverse and axial macrozones. In the centre of the billet, the radial blue type gives rise to a dominant pole at the centre of the  $\{10\bar{1}0\}$  pole figure and blue macrozones occupy the greatest portion of the map. A smaller amount of the axial red type is also present in the centre of the billet but the weaker local textures of the red macrozones means there is only a weak pole at the centre of the  $\{0002\}$  pole figure. As one moves from

the centre of the billet to the edge, the relative amounts of the two types of macrozone change, so that at the edge of the billet the dominant macrozones are axial. This means that the pole at the centre of the  $\{10\bar{1}0\}$  pole weakens, while the pole at the centre of the  $\{0002\}$  pole figure strengthens and red macrozones occupy the greatest portion of the maps.



**Figure 8.** Low resolution orientation image maps from the EBSD analysis.

Another noticeable feature of the global billet textures is that they do not have fibre symmetry about the billet axis. The texture that most closely resembles a fibre is in the centre of the billet (specimens 2 and E). Here, the ring of intensity at the edge of the  $\{0002\}$  pole figures reflects how the c-axes in the transverse macrozones have a range of directions in the transverse plane. However, there is higher intensity in directions which are within approximately  $\pm 45^\circ$  of the arbitrary R2 axis, which shows that there is preferential alignment of the transverse macrozones in these directions. Further away from the centre of the billet, there is a stronger preferential alignment of the c-axes in the transverse plane. In many locations in the cross-section, there is a similar direction for this preferred alignment, with the c-axes lying in a radial direction approximately  $30^\circ$  clockwise from the arbitrary R2 axis. Where the



preferential alignment is strongest, a band of intensity connects the  $\{0002\}$  poles at the edge of the pole figure, with the  $\{0002\}$  pole in the centre.

As well as the alignment in the pole figures, there is also a subtle alignment of the macrostructure in some of the low resolution EBSD maps (Figure 8), most notably in specimens 1, 3, 5 and 6. The direction of this macrostructural alignment is similar and corresponds to the direction of the bands of intensity in the  $\{0002\}$  pole figures i.e. a radial direction approximately  $30^\circ$  clockwise from the arbitrary R2 axis. These results indicate that in addition to the very strong primary alignment of the macrostructure along the billet axis, in some locations in the billet, there is also a secondary alignment of the macrostructure in a specific direction in the transverse plane.

#### 4. Discussion

The results of the low resolution EBSD analysis (Figure 8) have revealed that the billet contains macrozones throughout the cross section. The macrozones are related to prior colonies of aligned  $\alpha$  lamellae, which have the same crystallographic orientation and as a result tend to deform and globularise in a similar manner, thus maintaining similar crystallographic orientations in the globularised  $\alpha$ p grains. The macrozones are large columnar shaped regions elongated along the billet axis. In certain locations of the billet, some macrozones also show a secondary elongation in the transverse plane.

Regardless of the location in the cross section, the  $\alpha$  phase texture of a macrozone is always composed of a single hcp component, with varying degrees of spread up to around  $30^\circ$ . This is in agreement with macrozone textures reported by Thomas [5] and Pilchak [3] but differs from the macrozones analysed by Germain et al. [1], which consisted of a dominant component and in addition, several weaker ones. The absence of the weaker components in this study and Thomas [5] can be explained by the different proportions of  $\alpha$ p and  $\alpha$ s in the billet that was analysed by Germain et al. [1]. The billet in the work of Germain et al. [1] contained 70%  $\alpha$ s, and by analysing the contribution of the  $\alpha$ p and  $\alpha$ s separately, it was shown that the  $\alpha$ s gave rise to the weaker components, while the dominant component was due to overlapping of a single  $\alpha$ p component and the main  $\alpha$ s component. In the present study, the highest volume fraction of  $\alpha$ s was only 30% at the edge of the billet, which is too low to produce significant secondary components in the macrozone textures. Consequently, the high volume fraction of  $\alpha$ p in the billet means that the overall  $\alpha$  texture only shows the orientation of the single  $\alpha$ p component and thus a separation of the contribution of the  $\alpha$ p and  $\alpha$ s was not considered to be necessary for the macrozone textures in this work.

Analysis of the orientation image maps in conjunction with measurements of global texture, have shown that there is a tendency for the macrozones to have certain preferred orientations. The majority of macrozones can be divided into two types: axial and transverse. In axial macrozones, the c-axes are aligned with the billet axis, which means that the basal  $\{0002\}$  planes lie parallel to the transverse plane. In the IPF maps obtained in the transverse plane, the axial macrozones appear as clusters of red grains. The individual  $\alpha$ p grains in the axial macrozones tend to be plate shaped with the plane of the plates parallel to the billet axis. This means that the c-axis direction tends to lie in the plane of the plate shaped grains.

In transverse macrozones, the c-axes lie in the transverse plane i.e. at  $90^\circ$  to the billet axis. The largest and sharpest macrozones in the billet were of this transverse type and also had a  $\{10\bar{1}0\}$  plane lying in the transverse plane, thus appearing in the transverse plane IPF maps as clusters of blue grains. The individual  $\alpha$ p grains in the blue transverse macrozones tend to be plate shaped, with the plane of the plates parallel to the billet axis and aligned in the same transverse direction as other  $\alpha$ p grains within the same macrozone. The  $\langle 10\bar{1}0 \rangle$  direction and the c-axis direction tend to lie in the plane of the plate shaped grains.

The macrozones reported by Germain et al. [1] in Ti-834 billet and Bantounas et al. [4] in Ti-6Al-4V bar were of the transverse type. Thomas [3], in Ti-834 billet reported mainly the transverse type but also one instance of the axial type. In this study, it was found that the relative amount of axial and transverse macrozones varies depending on the location in the cross-section. The most obvious trend is the centre to edge variation in the relative amounts of the two types of macrozone. The centre of the

billet consists mainly of the transverse type, which have  $\{10\bar{1}0\}$  planes lying in the transverse plane, and a lesser amount of the axial red type. As one moves from the centre to the edge of the billet, the relative amounts change so that the edge contains more of the axial macrozones and a lesser amount of the blue transverse type. This work suggests that axial macrozones are much more significant than suggested by previous studies, particularly at the edges of a billet.

## 5. Conclusions

The crystallographic texture of a cross-section of Ti-834 billet has been investigated and the following conclusions can be drawn:

1. The billet contained microtexture heterogeneities (macrozones) throughout the billet cross-section.
2. The  $\alpha$  phase texture of a typical macrozone is composed of a single hcp component, with varying degrees of spread up to around  $30^\circ$ .
3. Macrozones are typically columnar shaped regions elongated along the billet axis. In certain locations of the billet, some macrozones also show a secondary elongation in the transverse plane.
4. Macrozones are typically 100-1000 $\mu\text{m}$  in diameter in the transverse plane and up to several thousand microns in length.
5. The majority of macrozones can be classed as either axial (c-axis parallel to the billet axis) or transverse (c-axis perpendicular to the billet axis).
6. In the centre of the billet cross-section, the global texture was dominated by a fibre-like  $\{10\bar{1}0\}$  texture due to a dominance of transverse macrozones. At the edge, there was a greater proportion of axial macrozones which gave rise to an additional  $\{0002\}$  component.
7. In this product form, areas analysed using EBSD were large enough for representative global textures to be acquired.

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