Microtextures and grain boundary misorientation distributions in controlled heat input titanium alloy fusion welds

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Abstract. Microstructures, macrotextures and microtextures in commercial purity titanium and Ti-6Al-4V fusion welds produced by the InterPulse gas tungsten constricted arc welding (GTCAW) technique have been characterised. At the cooling rates associated with the InterPulse technique, α variants sharing a common (120) pole are found to cluster together into groups within prior β grains, leading to large areas where all variants are separated by a misorientation of 60º. These present potential easy slip paths, hence increasing the “effective structural unit size.” Characterisation of these microtextures may provide new insight into microtexture-properties relations and the mechanisms of microtextural evolution.

1. Introduction
Titanium alloys are one of the most widely used groups of materials in structural engineering applications. However, joining them by fusion welding is still seen as difficult. As such, there is an ongoing need for development of improved welding techniques and characterization of the welds which they produce. The work here shows that textural and microtextural characterization is an essential part of this, and may provide insight into properties which remain to be fully understood.

One area of development in the search for improved titanium weld properties has been towards constricted arc processes. Gas tungsten constricted arc welding (GTCAW), and specifically the InterPulse technique of the Vacuum Brazing Consultants (VBC) group [1] has shown the potential for high quality results. The InterPulse technique uses magnetic constriction and high frequency modulation of the arc current (20,000Hz) to greatly reduce the overall heat input compared to conventional gas tungsten arc welding.

It has long been known that when characterizing titanium in general, texture should not be ignored. More recently, with the advent of techniques such as X-ray diffraction (XRD) for texture analysis, this importance has been increasingly demonstrated. Moreover, with analysis by electron backscatter diffraction (EBSD) it has now become possible to link microstructure and texture together - so-called “microtexture” - to provide new insight into materials processing-structure-properties relationships. Recent application of these techniques to titanium alloy welds [2] has highlighted the importance of microtextural characterization of fusion welds. In titanium alloys, microtextural characterisation takes on particular importance because the α to β phase transformation, which occurs according to the Burgers orientation relationship {000}α // {110}β and <110>α // <111>β [3], is often biased towards the
preferential selection of certain α variants (so called “variant selection”). Of particular significance are the findings that the formation of titanium weld microtextures may be related to the cooling rate of the fusion zone [2].

2. Experimental
Welds were produced in 1.2mm thick Ti-6Al-4V and Cp-Ti sheet using an InterPulse 150 narrow bead manual TIG precision welding system. Welding parameters typically consisted of an arc voltage of 9V, average current of 20-40A and a linear travel speed of 50mm·min⁻¹. These resulted in heat inputs of ~240 J·mm⁻¹ and consequent cooling rates of ~5ºC·s⁻¹ at the β-transus temperature. Some welds were produced using low frequency current pulsing in addition to the 20,000Hz InterPulse waveform. Characterization was performed by polarized light microscopy, electron backscatter diffraction (EBSD), X-ray diffraction (XRD) and microindentation hardness measurements.

3. Results
The use of different welding parameters had a significant effect on the overall microstructures and textures in different welds. Figure 1 shows polarized light micrographs of two welds produced with an identical heat input, but using different welding parameters, intended for (a) high penetration and (b) structure build up. The use of polarized light gives textural contrast between different basal plane orientations because of the anisotropy of the unit cell of the hexagonal α phase.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** (Colour online) Polarized light micrographs of the fusion zone in InterPulse welds produced using Cp-Ti base metal and Ti-6Al-4V filler wire, with welding parameters intended for: (a) high penetration, (b) structure build up. The area outlined by the box in (a) corresponds to the polarized light micrograph and orientation map in figure 2. (NB The images are montages of more than one micrograph).

While the overall microstructures and textures vary significantly between these and other welds examined, there are important microtextures which were found to be present in all of the welds (although to differing extents). An example is highlighted in figure 2, showing an orientation map from EBSD and a corresponding polarized light micrograph. In the orientation map, prior β grain boundaries are outlined by solid black lines. These boundaries have been determined by isolating an area in the orientation map suspected to be a single prior β grain and examining the (0001) pole figure for that region. For a single prior β grain, the pole figure should, because of the Burgers relationship [3], show six strong peaks. Within the prior β grain in the centre of the map, certain α variants have clustered into “sub-grains,” which are divided by dashed white lines. For two of the sub-grains, the α texture components present have been identified (using the INCA Crystal software “autotexture” routine), and their respective (0001) and (1120) pole figures are displayed. These show that in each sub-grain, there are three α variants, with (0001) poles which lie 60º apart on a great circle. Hence these variants share a common (1120) pole (circled) and therefore a common (1120) direction.
4. Discussion

The finding that α variants within sub-grains are separated by a grain boundary misorientation of 60º and share a common [1120] direction is significant. This is because <1120> is the slip direction in α titanium. Hence if slip were to occur within the sub-grain, it would be expected to proceed relatively more easily than in a region with more mixed grain boundary misorientations. Where the grain size is small, such as in the fusion zone, these grain boundaries may take on great importance in determining the mechanical properties of the weld.

![Figure 2](image)

**Figure 2.** (Colour online) (a) Orientation map from EBSD showing sub-grain clustering. Prior β grain boundaries are outlined by black solid lines and sub-grain clusters are divided by dashed white lines. (b) and (c) show texture components within the two arrowed sub-grains. The associated pole figures show that each sub-grain consists of three texture variants, whose (0001) planes lie 60º apart on a great circle and hence the variants share a common (1120) pole (circled). (d) Polarized light micrograph (montage of two images) corresponding to the central area in (a).

The “clustering” into sub-grains has been observed in the past in plasma welds [2] and was proposed as an explanation of higher than expected impact toughness in those welds. In this work, the significance in practice has been observed directly by performing microindentation hardness measurements into sub-grains. These generally showed a lower hardness compared to other more “random” microtextural regions, although further work is required in this aspect.

As proposed by Merson [2], the sub-grain clustering effect appears to be related to the cooling rate of the welding process, with it being able to predominate at intermediate cooling rates, such as those associated with plasma welding (investigated by Merson [2]) or the InterPulse welding examined here. A number of authors have supposed that the high occurrence of the 60º grain boundary misorientation must be related to some energetic favourability of this boundary type e.g. [2,4,5], although a full explanation of why has not yet been made. 60º is one of the five allowed grain boundary misorientations between α laths within a single prior β grain according to the Burgers relationship [6], but the proportions seen here are much higher than random and are associated with the sub-grain clustering effect.
In this work, a feature which frequently occurred in the microstructures/microtextures was the formation of laths into a distinct “triangular” arrangement, some examples of which are shown in figure 3. Analysis of the grain boundaries between these laths suggests that they are separated by the favourable 60° misorientation. The fact that the three laths in the triangle have grown thicker than others could suggest that the boundary is favourable in growth. On the other hand, the fact that many laths have formed together in the sub-grains could suggest it is related to nucleation. Further investigation is required here.

Figure 3. (Colour online) (a) Polarized light micrograph from the fusion zone of an InterPulse weld showing the formation of α laths into clear triangular morphologies. (b) Fusion zone orientation map from EBSD showing a “triangle” cluster (not corresponding to (a)). (c) Isolated texture component map for the sub-grain cluster in (b).

Importantly, it was found in this work that the clustering effect need not be isolated to small areas. Indeed, when the prior β grain labelled A in figure 2 is run through the INCA Crystal autotexture routine, it is found to possess the “sub-grain microtexture.” Correlating the orientation map in figure 2 with the polarized light micrograph in figure 1(a) shows that this prior β grain spans the entire width of the fusion zone, and hence is highly significant in terms of the overall weld macrostructure. A strong macrotexture was indeed confirmed by XRD, although these results are not shown here.

5. Conclusions
This work has shown that consideration of macrostructure, microstructure, texture and microtexture are necessary in order to characterize titanium alloy fusion welds. Important microtextures which may explain as yet poorly understood mechanical properties have been found and characterized, and it is proposed that their occurrence and nature are strongly related to the cooling rate associated with the welding process. The findings warrant further work in this area, which may yield greater understanding of both phase transformations and mechanical properties in titanium alloy fusion welds and in titanium alloys in general.

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