Abstract

Commercially pure α-Titanium (Grade-II) has a hexagonal close-packed (hcp) crystal structure. This crystal structure possesses inherent anisotropy leading to complex deformation behaviour. Even though α-Ti is considered to have high stacking fault energies (SFE) in the prismatic, basal and pyramidal slip planes. There are only two independent prismatic slips present at initial strains. The deformation is compensated by the evolution of $\{10\bar{1}2\}\langle 10\bar{1}\bar{1}\rangle$ extension and $\{11\bar{2}2\}\langle 11\bar{2}\bar{3}\rangle$ contraction twinning. At the same time, pyramidal and basal may become active at intermediate or higher strains. Interestingly there are very few research works that discuss these aspects of deformation mechanism and the effect on strain hardening behaviour, microstructure and texture evolution. Apart from this, microstructure, texture evolution, and strain hardening behaviour are directly influenced by (i) initial microstructure, including grain size, texture, deformation history and (ii) effect of strain path change is also required to be investigated for α-Ti. Moreover, the possibility to obtain microstructure with refined grains and desired texture in α-Ti are explored so that an optimized combination of strength, ductility and formability could be obtained. The present thesis is an attempt to address these issues. The thesis has been divided into eight chapters. Chapters 1, 2, and 3 are dedicated to the introduction, literature review, and research methodology. Subsequent chapters 4-8, deal with the experimental and simulation results, discussion, summary and conclusions.

In this investigation, the commercially pure Grade-II α-Ti was selected. The material was subjected to uniaxial compression $CD||ED$, $CD \perp ED$, open die multi-axial forging (ODMF), and multi-axial plane strain forging (MPSF) followed by cold rolling (CR). Further MPSF+CR samples were subjected to a heating and quenching process. A systematic analysis of microstructure and texture for initial and processed samples were performed by electron backscattered diffraction (EBSD) using a field emission gun scanning electron microscope (FEG-SEM). Bulk texture, dislocation density and crystallite size measurements were performed for the selected samples by X-ray diffraction and X-ray line profile analysis respectively. The experimental flow curve and deformation texture were validated by visco-plastic self-consistent modelling simulation. The details of experimental as well as simulation techniques used in the present investigation are described in chapter 3.

The deformation mechanism, strain hardening behaviour, and texture evolution during axial deformation have been investigated in Chapter 4. This chapter is divided into two

sections, sections 4.1 and 4.2. Section 4.1 covers Strain hardening behaviour and ex-situ quantitative microscopy. Section 4.2 emphasis the overall deformation behaviour.

Section 4.1 A typical sigmoidal nature of the flow curve observed during the uniaxial compression test was investigated in detail. Nature of flow cure was revealed that overall deformation accomplished by slip and deformation twin concurrently. The twin induced grain refinement phenomenon was observed by detailed microstructure investigations. Further, the effect twin induced grain refinement on the evolution of crystallographic texture and strain hardening response were studied in detail. The strain hardening rate curve could be distinguished into regions of twin and slip dominating zones. The double derivative plot could separate out regions of increasing and decreasing twin and slip activities. Microstructural features were shown and explained with help of Taylor (Orientation) factor (TF) maps, grain orientation spread (GOS) map, grain reference orientation deviation (GROD) map vis-à-vis the corresponding inverse pole figure (IPF) maps and crystallographic texture. The work indicates the preferential dominance of the slip and twinning modes at different strain levels in CP-Ti, leading to multiple stages of work-hardening.

In section 4.2, a detailed study to understand the reasons behind the domination of dislocation slip and twinning deformation modes at different strain levels and their effect on the microstructure and texture evolution was carried out. Whether the visco-plastic self-consistent – predominant twin reorientation (VPSC-PTR) approach could decipher these changes, and predict the sigmoidal shaped strain hardening curve, and texture evolution? The slip and twin activities provided by VPSC during deformation will give an insight into the changes in the deformation mechanism with strain. Results from VPSC were used as the strategy to partition the microstructures, obtain corresponding textures, and determine the volume fraction evolution of the extension and contraction twin domains with deformation and their corresponding microstructural and textural features discussed vis-à-vis crystal plasticity simulations.

The evolution of extension and contraction twinning depends upon the initial orientation with respect to the loading direction. The formation of ET increases the texturally hard orientation and increase the strain hardening rate. The partition results showed that ET and CT occupy nearly 74% and 26% area of microstructure respectively. Such a large amount of secondary twinning might influence the texture as well as strain hardening behaviour of the material. Therefore, CT was focused exclusively. In chapter 5, the variant selection of CT and its effect on strain hardening were investigated in section5.1 and 5.2 respectively.

Section 5.1 investigates the CT variants nucleation and growth strategy via Schmid factor analysis statistically using 50 grains in which CT evolved. Further, the texture components evolved due to the CT variants in these grains were correlated and nomenclated. The crystallographic orientation of matrix and deformation-induced CT-variants are explained via lattice orientation, pole figure, and orientation distribution function (ODF). A small part of the analysis also explores the importance of symmetry operation during texture analysis. In section 5.2, the uniaxial compression test along the radial direction was investigated and compared vis-à-vis the compressive deformation along with ED. Microstructure investigations show that the initial orientation preferentially deforms primarily by CT evolution in this case instead of ET. Few grains with initial orientation preferable for the evolution of ET were also observed. Also, ET evolves in the CT domains with further deformation. The strain hardening behaviour of the material could be corroborated with the microstructure morphology including the misorientation angle distribution obtained from orientation imaging microscopy (SEM-EBSD). Apart from this, the VPSC simulation technique was used to obtain the CRSS ratio and slip/twin activities by matching the strain hardening response and texture evolution.

Further, the effect of deformation history, grain size, dislocation density, texture and strain path change on the strain hardening, microstructure and texture evolution was studied in Chapter 6. To replicate all these effects, conventional open die multiaxial forging (ODMF) is used to process the material. After every forging process, the change in the strain path helps to obtain an initial input texture away from the ideal end orientation for the axial compression. It is important to find out the strain hardening response during sequential X-Y-Z forging. The data were collected after each axial deformation to explore the mechanism of grain refinement associated with microstructural features and texture evolution. Moreover, deformation textures were simulated to obtained slip-twin activity to understand the strain hardening response and corroborated with microstructure and texture.

Finally, in Chapter 7, the scientific understanding developed from Chapters 4-6 was utilised to develop a new multiaxial plane strain forging process to obtain ultra-fine grains in Ti. Thereafter, the conventional rolling operation was used to convert UFG into nanostructure grain and form a thin sheet of Ti. Further, thin sheets were subjected to a heating and quenching cycle and obtained the desire microstructure and texture. The bulk mechanical properties such as yield strength, ultimate tensile strength, uniform elongation are corroborated with microstructure features and crystallographic texture. The final outcomes of the thesis have been summarized in Chapter 8.