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THE EFFECT OF ALUMINIUM ON DEFORMATION AND TWINNING IN ALPHA TITANIUM: THE ND CASE

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Abstract

The deformation behavior of binary Ti-Al model alloys (0 to 13at.%) has been observed during compression normal to the rolling direction with respect to the activity of $\{1\ 1\ \bar{2}\ 2\}$ compression twins but also the more common $\{1\ 1\ \bar{2}\ 0\}$ tension twin as well as the rarely seen $\{1\ 1\ \bar{2}\ 1\}$ tension twins. In-situ neutron diffraction loading experiments and EBSD microstructure analysis were used to qualify the impact of Al on twinning. The results show that for the given loading direction and starting texture, $\{1\ 1\ \bar{2}\ 2\}$ and $\{1\ 1\ \bar{2}\ 0\}$ twinning are similarly common in commercially pure Ti, while only small additions of Al result in a dramatic decrease in $\{1\ 1\ \bar{2}\ 2\}$ compression twinning. In contrast, dramatic reductions of $\{1\ 1\ \bar{2}\ 0\}$ twin fractions are only observed above 10at.% Al and with an ageing treatment to promote Ti_3Al formation. Al addition until 10at.% makes $\{1\ 1\ \bar{2}\ 1\}$ twinning more likely, but Ti_3Al formation seems to deactivate this twin system. The role of slip on twinning is discussed.

Introduction

A fundamental understanding of impact of alloying on the deformation behaviour is the base for future alloy development. To date, the difference in twin activities between commercially pure Titanium (Ti) and industrial alloys such as Ti6Al4V or Ti5Al2Sn are still not clearly understood [Prakash 2010, Li 2013]. Deformation twinning in Ti alloys increases ductility and alters the texture significantly during forming, especially at low temperature where twinning is more likely. Therefore, the knowledge of twin activity during deformation in different alloys and conditions enables the producer to alter the processing route to tailor microstructures and textures to the customers needs. Furthermore, twins induced by machining have been connected with an accelerated diffusion of oxygen and formation of the alpha case at elevated temperature, and therefore, detrimental to performance under fatigue loading [Thomas 2009]. With Al and O as the most efficient strengthening element in Ti alloys, their effects on deformation modes have been investigated in the past but only limited attention was given to deformation twinning. Single crystals deformation experiments [Williams 2002] suggest that twinning becomes less likely with increasing Al content, but no such conclusions were made on polycrystalline material. The way Al increases the c/a ratio [Fitzner 2014] and hence changes

the twin shear strain suggests that tensile twinning should become easier but compression twinning more difficult with increasing Al content [Yoo 1981]. Williams further suggests that basal $\langle a \rangle$ -slip becomes relatively easier to prismatic $\langle a \rangle$ -slip at 11at% Al, which can be explained by the increased packing on the basal plane with increasing Al content. Williams results also show that $\langle c+a \rangle$ slip becomes more difficult with increasing Al concentration and slip occurs more planar. An increase of slip planarity has been reported for polycrystalline material once α_2 -precipitates are present [Truax 1974, Neeraj 2001]. Transmission electron microscopy and neutron diffraction measurements at WISH, ISIS indicate short range ordering or very early signs of α_2 -formation at 10at.% Al (6wt.%) for the present alloys [Fitzner 2014]. Van de Walle explains the slip localisation with ordering of Ti_3Al by the reduced energy required to re-order the structure by tailing dislocations using first principles calculations [Van de Walle 2002]. However, there is no comprehensive study of how Al impairs the twin activity at such concentrations.

In order to understand the effect of Al on deformation twinning and the reported drop of twin activity around 10at.% Al, binary alloys have been investigated in the present work. Compression experiments have been carried out on hot rolled polycrystalline binary Ti-alloys with different Al contents along the normal direction. Prior to deformation, the alloys were processed with the aim to have similar recrystallised starting microstructures and textures to allow meaningful comparisons between the alloys. Compression tests were characterised at 9% strain by means of electron backscatter diffraction (EBSD) and in-situ neutron diffraction analysis.

Table.I: Chemical composition of the model alloys in this study, their grain size (GS) and lattice parameters.

Alloy	Al wt%	Al at%	O ₂ ppm	GS μm	$\langle a \rangle$ nm	$\langle c \rangle$ nm
Ti-0Al	0.00	0.0	507	94	2.949	4.683
Ti-3Al	2.00	3.49	474	82	2.942	4.681
Ti-7Al	3.90	6.67	413	73	2.935	4.678
Ti-10Al	5.88	10.01	756	71	2.929	4.675
Ti-10Al ^{aged}	5.88	9.99	567	77	2.928	4.673
Ti-13Al	7.85	13.13	377	78	2.925	4.669

Methods, Results and Discussion

Starting material: Five model Ti alloys with Al contents up to 8wt% (13at%) were cast, forged and cross-rolled to axis-symmetric bars of 14x14x260mm by TIMET, UK. The rolling and annealing temperatures were adjusted to produce similar grain size distributions with a mean value of around 80 μ m for each alloy, as detailed in Table I. EBSD orientation maps and pole figures calculated from measurements covering an area of 4mm² are shown in Fig.1 a) and b) for Ti-0Al and Ti-10Al. The {0002} pole figures exhibit a band of high intensity perpendicular to the original rolling direction (RD) and only little intensity in RD. The relatively weak {1 0 $\bar{1}$ 0} fibre present in Ti-0Al gradually changes to a distinct texture component with increasing Al content, which suggests increased basal slip activity [Rosi 1953]. Lattice spacing of <a> and <c> parameter were determined on the neutron diffraction beam line ENGIN-X based at the neutron spallation source ISIS in the UK.

Fig.1: a) Microstructure and b) texture for undeformed Ti-Al alloys with the compression axis parallel to ND_{II}.

Fig.2: Compressive flow curves of binary Ti-Al alloys with LD/ND

Mechanical properties:

Cylindrical compression samples with a diameter of 6mm and 9mm length, with the loading axis parallel to the original normal direction (ND_{II}) were compressed under quasi-static loading to 9% strain. The yield strength increases almost linearly with Al content up to 10at% but only marginally with further Al addition, Fig. 2. The small strength increase from Ti-10Al to Ti-13Al can

be understood as an effect of more intense α_2 formation. Interestingly, ageing of Ti-10Al does in fact slightly decrease the yield strength, which might suggest that the loss of Al from the matrix has a greater effect on the strength of the alloy than a slight change of α_2 -precipitates (higher volume fraction of slight coarsening). The work hardening capacity is highest in Ti-7Al and decreases again with a further increase in Al content, particularly in the aged condition of Ti-10Al.

Deformation microstructure and texture: Fig. 3 shows EBSD maps of samples compressed to 9% strain, cross-sectioned and polished. Band contrast maps in Fig. 3 a) emphasise the fraction of twin boundary types, while Fig. 3 b) shows the same area in inverse pole figure colouring to represent orientations of parent grain and twin. In Ti-0Al {1 0 $\bar{1}$ 2} < $\bar{1}$ 0 1 1> tensile twins (red or black boundaries, respectively) and {1 1 $\bar{2}$ 2} <1 1 $\bar{2}$ 3> compression twins (blue or white boundaries, respectively) are almost as likely, but {1 1 $\bar{2}$ 1} < $\bar{1}$ 1 2 6> tensile twins (green or grey boundaries, respectively) occur seldom and are very narrow. The reduced frequency of {1 0 $\bar{1}$ 2} twin boundaries in Ti-3Al compared to Ti-0Al is probably a consequence of the micro texture of the region studied, consisting mainly of hard grains with their c-axis close to the LD, unlikely to deform by tension twinning but more likely to deform by compression twinning. Even more remarkable therefore is that {1 1 $\bar{2}$ 2} compression twins occur less frequent in Ti-3Al and are narrower compared to the rather homogenous texture patch of Ti-0Al. Not a single compression twin is evident at higher Al contents. Instead {1 1 $\bar{2}$ 1} tensile twins become more frequent in Ti-7Al and even exceed 10 μ m width in Ti-10Al.

However, further Al addition or ageing of Ti-10Al, designated Ti-10Al^a in Fig 3, entirely deactivates {1 1 $\bar{2}$ 1} tensile twins and only {1 0 $\bar{1}$ 2} twins are active in Ti-13Al and aged Ti-10Al. The small scanned areas and dramatic variations in the local texture forbid meaningful quantification of twin fractions but support, in principle, previous findings on the same alloys when loading along the RD [Fitzner 2013 1] or 45° between RD and ND [Fitzner 2013 2]. Along these other directions, the frequency of {1 0 $\bar{1}$ 2} twins is slightly increased with initial addition of Al, but reduces dramatically in excess of 10at.% Al, related to the onset of α_2 -formation. The most important finding in the current study is the strong suppression of compression twinning with increasing Al content. A lack of compression twinning has implications for the texture evolution during compression along ND, a loading condition typical of operations such as rolling. At ambient temperature only {1 1 $\bar{2}$ 2} compression twins can reduce 0002 pole intensity along the LD and increase it perpendicular to the LD. As such texture weakening does not occur in alloys containing 7at.% Al or more, formability is impaired. Even though {1 1 $\bar{2}$ 1} tensile twins alter the texture in recrystallised Ti-7Al and Ti-10Al, first they sharpen the basal texture and second their low volume fraction below 2% has little impact on the global texture. With {1 0 $\bar{1}$ 2} twinning as dominant system in Al containing alloys the basal texture sharpens with increasing plastic strain, as the 0002 pole within the twin is rotated by 86° into the LD.

Fig. 4 illustrates the textures after 9% compression for Ti-0Al and Ti-10Al in comparison to the RX state in Fig. 1 b). The 0002 pole figures before and after deformation of Ti-0Al are essentially identical, but the {1 0 $\bar{1}$ 0} planes become more randomised with deformation. The 1 0 $\bar{1}$ 0 pole figure in Ti-10Al remains relatively unchanged, but the 0002 intensity weakens along ND_I and strengthens close to LD due to {1 0 $\bar{1}$ 2} twinning.

Fig.3: Microstructure after compression to a true strain of 0.09 parallel to ND_{II} with twin boundaries marked in the a) Band contrast maps and IPF maps according to: $\{0002\} \langle \bar{1}011 \rangle$ tensile twin system (TT1) in red or black boundaries, $\{21\bar{1}6\} \langle \bar{2}116 \rangle$ tensile twins (TT2) in green or grey boundaries and $\{10\bar{1}1\} \langle 1012 \rangle$ compression twin system (CT1) in blue or white, respectively.

Fig.4: Deformation textures at a compressive strain of 9% along ND_{II} and indications of the axial and transverse coverage at Engin-X.

Texture and lattice strain evolution from in-situ neutron diffraction:

Loading was additionally carried out incrementally up to about 9% plastic strain on ENGIN-X on 8x12mm cylinders, while diffraction measurements (30 μA, 24min under optimal beam conditions) were undertaken in unloaded condition (at -15 MPa) to avoid cold creep. The purpose of the in-situ loading experiments was to understand the effect of twinning on the

residual elastic lattice strain response of individual grain families and the related texture change, both determining the macroscopic material behaviour. Fig. 5 shows the intensity change of the 0002 pole in a) axial and b) transverse direction. The overall dominant $\{10\bar{1}2\}$ twin orientates the 0002 pole into the LD and consequently increases the 0002 intensity in the axial detector, as shown in Fig. 4. Thus Fig. 5 a) shows significant activity of $\{10\bar{1}2\}$ twinning in Ti-0Al and in Ti-3Al and only moderate activity in Ti-7Al and Ti-10Al at strains below 3%. At strains above 3% the 0002 intensity increases more noticeably in Ti-7Al and in Ti-10Al and indicates more $\{10\bar{1}2\}$ twinning. In contrast in Ti-0Al and Ti-3Al the reduction in 0002 pole intensity above strains of 3% and 6%, respectively, indicates the activity of $\{11\bar{2}2\}$ compression twinning, confirming the EBSD analyses. Here one should remember that $\{11\bar{2}2\}$ compression twinning is the only deformation system which can decrease the basal intensity in LD spontaneously and increase the intensity 65° from the LD at the same time. The location of the transverse detector in relation to the starting texture is indicated in Fig. 4 and coincides with the original RD. Only Ti-0Al shows small 0002 pole intensity in the recrystallised condition before loading while none of the Ti-Al alloys shows any basal reflection along RD. Fig. 5 b) plots the change of the 0002 pole intensity in the transverse detector as function of the applied strain. Even though the transverse detector covers only a small angular range of possible $\{11\bar{2}2\}$ compression twins, data indicate activity from approximately 1% strain in Ti-0Al and from about 9% in Ti-3Al but not in the alloys of higher Al content, confirming the EBSD results and Fig. 5 a).

The residual (0002) tensile lattice strains recorded in axial direction ($\mu\epsilon_{0002}$) of the compression experiments has been plotted in Fig. 6. With the c-axis under compression, this grain family is well aligned for $\{11\bar{2}2\}$ compression twins and for the rather unlikely pyramidal $\langle c+a \rangle$ slip. $\mu\epsilon_{0002}$ first increases in all alloys up to about 1.3%. In Ti-0Al this is followed by a decrease of $\mu\epsilon_{0002}$ to about 3% plastic strain before $\mu\epsilon_{0002}$ increases again. After the elastic regime in Ti-3Al $\mu\epsilon_{0002}$ slightly decreases, while it barely changes in Ti-7Al and slightly increases in Ti-10Al. As mentioned above, in Ti-0Al only compression twinning is expected to cause such lattice relaxation. With the loss of compression twinning the ability to relax those grains fades, supporting the idea of $\langle c+a \rangle$ slip in this case. It should be kept in mind that neighboring grains of the 'hard' grain family are likely to be softer and can accommodate the global plastic deformation without the need to deform the hard grains themselves. However, it cannot be excluded that $\langle c+a \rangle$ slip unloads $\mu\epsilon_{0002}$ since it provides a shear elongation with a $\langle c \rangle$ component [Williams 2002].

The neutron diffraction data highlight $\{11\bar{2}2\}$ compression twin activity in Ti alloys with low Al content, which should improve formability due to the texture weakening and the release of (residual) intergranular lattice strains.

Interaction between slip and twinning

The changes in likelihood of different twin systems with increasing Al content links up with theoretical considerations on deformation slip and novel experimental studies on the interactions of slip and twinning. Prismatic slip was shown to precede $\{10\bar{1}2\}$ twinning [Fitzner 2014] and to become more difficult relative to basal slip with increasing Al content [Williams 2002]. In turn, basal slip becomes more likely [Williams 2002] and was observed together with $\{11\bar{2}1\}$ tensile twins by digital image correlation [Fitzner 2014]. Therefore the reduced activity

Fig.5: Intensity development of basal pole in a) axial and b) transverse direction during compression at Engin-X, NB: Legend is shared.

Fig.6: Lattice strain development on the basal plane in axial direction during compression at Engin-X

of $\{1\ 0\ \bar{1}\ 2\}$ tension twins and the increased likelihood of $\{1\ 1\ \bar{2}\ 1\}$ tension twins in Ti-10Al can be understood as result of the facilitated basal slip. While the c/a ratio does not seem to affect the likelihood of tension twinning, compression twinning does become more difficult with increases c/a ratio, in example at higher Al content, as predicted by Yoo from the theoretical twin shear. Slip trace analyses by Paton and Backofen [Paton 1970] and by Fitzner [Fitzner 2014] suggest that pyramidal $\langle c+a \rangle$ slip is required to initiate $\{1\ 1\ \bar{2}\ 2\}$ compression twinning, which is considered less likely with increasing Al addition. The combination of increasing twin shear and more difficult dislocations for compression twin initiation can rationalise the reduced activity of $\{1\ 1\ \bar{2}\ 2\}$ compression twins.

Conclusion

Compression studies have been carried out on Ti-Al alloys with contents of 0, 3, 7, 10 and 13 at.% normal to the original rolling direction. A combination of in-situ neutron diffraction loading experiments, post mortem microstructure and texture characterisation by EBSD has demonstrated that:

- The relatively high activity of $\{1\ 1\ \bar{2}\ 2\}$ compression twins is strongly reduced by the addition of Al to Ti, until no compression twinning occurs at concentrations above 7at.% Al, rationalised by the higher activity of $\langle c+a \rangle$ slip and twin shear at low Al concentrations.
- Within the Ti-Al alloys $\{1\ 0\ \bar{1}\ 2\}$ tensile twinning is dominant but occurs far less frequently at concentrations above 10at.% Al, rationalised by the higher activity of $\langle c+a \rangle$ slip and twin shear at low Al concentrations.
- $\{1\ 1\ \bar{2}\ 1\}$ tension twinning occurs rarely in Ti-0Al, but more frequently with increasing Al content until 10at.%, while it is not active in Ti-13Al and aged Ti-10Al, rationalised by the increased activity of basal slip.

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References

- FITZNER-1, A., QUINTA DA FONSECA, J., PREUSS, M. & THOMAS, M. 2013. The effect of Aluminium on Deformation by twinning in Alpha Titanium. In: KHAN, A. S., ed. Plasticity '13, 2013 Nassau. A. Khan, 4-6.
- FITZNER-2, A., PREUSS, M., QUINTA DA FONSECA, J., KELLEHER, J., PRAKASH, D., THOMAS, M. & ZHANG, S. Y. The Effect of Aluminium on Deformation and Twinning in Alpha Titanium: The 45° Case. Materials Science Forum, 2013. Trans Tech Publ, 549-553.
- FITZNER, A. 2014. *Effect of alloying elements on Twinning in alpha Titanium alloys*. PhD, University of Manchester.
- LI, H., MASON, D., YANG, Y., BIELER, T., CRIMP, M. & BOEHLERT, C. 2013. Comparison of the deformation behaviour of commercially pure titanium and Ti5Al2.5 Sn (wt.%) at 296 and 728 K. *Philosophical Magazine*, 1-21.
- NEERAJ, T., HOU, D. H., DAEHN, G. & MILLS, M. 2000. Phenomenological and microstructural analysis of room temperature creep in titanium alloys. *Acta Materialia*, 48, 1225-1238.
- PRAKASH, D., DING, R., MOAT, R., JONES, I., WITHERS, P., FONSECA, J. & PREUSS, M. 2010. Deformation twinning in Ti-6Al-4 V during low strain rate deformation to moderate strains

at room temperature. *Materials Science and Engineering: A*, 527, 5734-5744.

-ROSI, F., DUBE, C. & ALEXANDER, B. 1953. Mechanism of plastic flow in titanium determination of slip and twinning elements. *Journal of Metals*, 5, 257-264.

-THOMAS, M., LINDLEY, T. & JACKSON, M. 2009. The microstructural response of a peened near- α titanium alloy to thermal exposure. *Scripta Materialia*, 60, 108-111.

-TRUAX, D. & MCMAHON, C. 1974. Plastic behavior of titanium-aluminum alloys. *Materials Science and Engineering*, 13, 125-139.

-VAN DE WALLE, A. & ASTA, M. 2002. First-principles investigation of perfect and diffuse antiphase boundaries in HCP-based Ti-Al alloys. *Metallurgical and materials transactions A*, 33, 735-741.

-WILLIAMS, J. C., BAGGERLY, R. G. & PATON, N. E. 2002. Deformation Behaviour of HCP TiAl. *Metallurgical and Materials Transactions A*, 33A, 837-850.