β RECRYSTALLISATION CHARACTERISTICS OF α + β TITANIUM ALLOYS FOR AEROSPACE APPLICATIONS

Michael Allan[1], Matthew Thomas[2], Jeffery Brooks[3], Paul Blackwell[1]

[1]AFRC (Advanced Forming Research Centre) 85 Inchinnan Drive; Renfrew, PA4 9LJ, Scotland
[2]TIMET - Witton, The Hub, Holford Road, Witton; Birmingham, B6 7BJ, England
[3]PRISM[2], IRC Netshape Lab - Dept. of Metallurgy & Materials, The University of Birmingham, Edgbaston; Birmingham, B15 2TT, England

Keywords: Recrystallisation, Ti-6Al-4V, Timetal 575.

Abstract

To investigate the β recrystallisation characteristics of established α + β alloy Ti-6Al-4V and novel α + β alloy Timetal 575 (Ti575), twelve 100mm diameter double cone samples were α + β forged, sectioned then heat treated in the β phase field. The double cone geometry chosen provided a gradient of strain in each sample with a strain profile provided by output from a finite element modelling package. The matrix of tests covered three forging temperatures and two deformation rates and was followed by heat treatments to two temperatures for two different times at temperature generating a recrystallised microstructure as a function of these parameters. The extent of microstructural refinement for both alloys was analysed using optical microscopy of the as-received and recrystallised microstructure.

Introduction

Titanium alloys have been employed in the aerospace industry for decades and they continue to meet the rigorous demands of critical aero-engine components. This longevity is owed to their low density, corrosion resistance and configurable mechanical properties optimised through carefully selected thermomechanical processing routes. For safety, critical rotating parts such as fan discs require optimal fatigue performance. In particular, strength and resistance to dwell fatigue are essential. Although Ti-6Al-4V has met these operating requirements the demands of industry to optimise performance and efficiency has led to the development of alloy chemistries designed for specific roles.

The novel titanium alloy Ti575 is one such α + β alloy recently developed by TIMET specifically for future fan disc applications. It has already demonstrated improved tensile strength and static and low cycle fatigue strength compared to Ti-6Al-4V while retaining a comparable density and ductility [1]. Crucially it has thus far proven insensitive to the dwell fatigue phenomenon and exhibits improved fatigue performance over Ti-6Al-4V [1] and the near-α alloy Timetal 834 [2]. This promising performance has led to further investigation of the alloys primary processing parameters to improve full scale production knowledge.

The manufacturing route for these alloys begins with the 'β-workout' reduction of the cast ingot above the β transus temperature. Subsequent 'pre-strain' forging in the α + β phase field refines the microstructure prior to a β recrystallisation heat treatment. The lamellae produced during cooling from β recrystallisation are broken down into the globularised primary α_p grains found in the bi-modal microstructures of many final alloy applications. Large regions of similarly crystallographically orientated α_p grains originating from the β recrystallisation stage can be retained throughout α + β processing and can dictate the lower property bounds of an alloy [3]. These large effective structural units contain long slip lengths and are detrimental to dwell fatigue performance and crack propagation resistance in particular.

A number of publications have investigated β recrystallisation during hot working in the β phase field [4–6] however no publication could be found examining the effect of the α + β pre-strain parameters on the subsequent β recrystallisation characteristics which this work investigates. Large double cone samples are employed due to the coarse microstructural conditions and to provide a profile of strain in one sample, reducing the volume of forgings required. A number of studies have successfully utilised double cone samples to investigate microstructural evolution and recrystallisation characteristics in titanium alloys with varied microstructural conditions [7, 8].

Experimental Procedure

The chemical compositions of the commercial Ti-6Al-4V alloy and the novel Ti575 alloy used in this work are provided in Table 1 below. The β-transus for these alloys is approximately 1000°C and 960°C respectively.

Table 1: Chemical compositions for Ti-6Al-4V and Ti575 used in this study.

	Al	V	Fe	Si	C	N	O	Ti
Ti-64	6.47	4.07	0.17	-	0.10	0.01	0.20	Bal.
Ti-575	5.3	7.7	0.25	0.5	0.01	0.01	0.18	Bal.

The Ti-6Al-4V material was sourced from the intermediate stage of manufacturing process in the form of six 120x100x120mm blocks. Microstructural characterisation of block faces revealed 2.6 - 5.8mm average and 11.1 - 31.4mm maximum prior-β grain diameters. Significant elongation along the billet axis was apparent with prior-β grains up to 80mm in length at an 8:1 aspect ratio. Examples of characterised block faces from the billet face (Figure 1a) and along the billet axis (Figure 1b) are presented with traced coarse α_{GB} at prior-β grain boundaries for clarity. Lath width varied from 0.5 - 3μm.

The six Ti575 120x100x120mm blocks were only available from a later intermediate stage so a vacuum heat treatment was employed to coarsen the prior-β grain size and reproduce the α colony and lath characteristics of the Ti-6Al-4V material. Figure 2 shows a 40x40mm section of this heat treated material with α_{GB} traced for emphasis. The homogeneous as-received material exhibited 1.34 mm average and 4.0mm maximum diameter which coarsened to 1.97mm and 5.47mm average and maximum diameter respectively. Lath width was consistent with the Ti-6Al-4V material.

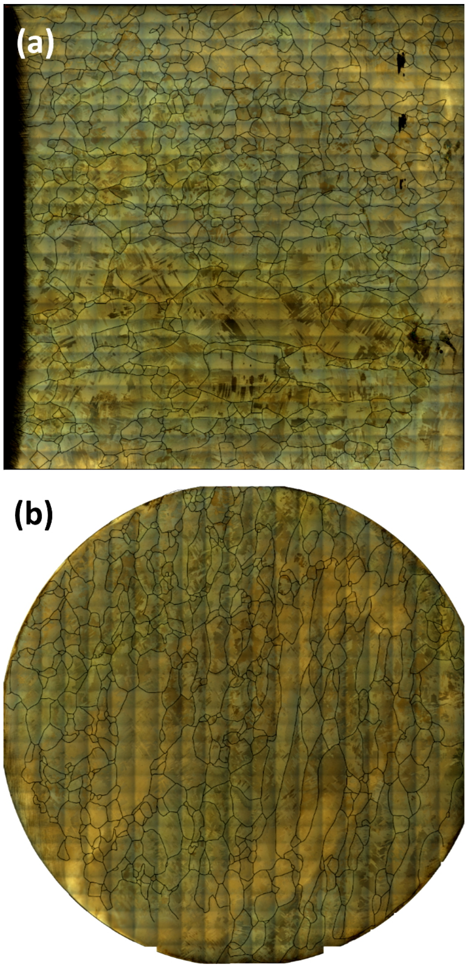

Figure 1: Ti-6Al-4V starting material. Macro view of (a) billet face (100x100mm) and, (b) along billet axis (100mm diameter).

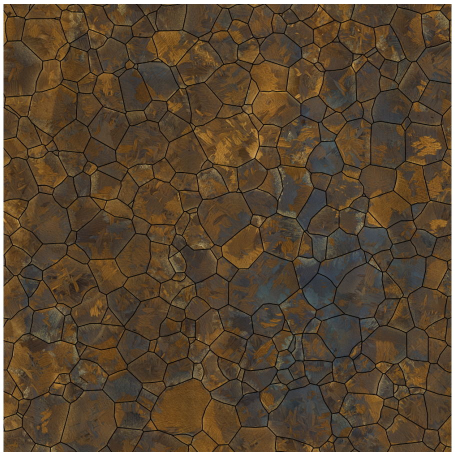

Figure 2: Ti575 vacuum heat treated starting material (40x40mm).

Double cone samples 80mm in height and 100mm major, 40mm minor diameter were coated with a Deltaglaze FB417 glass lubricant and held at forging temperature for a minimum of 90 minutes prior to forging. Compression tests were completed using a 500T hydraulic press at approximately $0.05s^{-1}$ and a 2100T screw press at approximately $4.2s^{-1}$ with die temperatures of 450°C and 250°C respectively. Samples were forged at one of three pre-strain temperatures (α/β_{T1}, α/β_{T2}, and α/β_{T3}) to either approximately 30mm for Ti-6Al-4V or 50mm final height for Ti-575. Initial test results from Ti-6Al-4V studies led to the change in final height for Ti575 tests with the purpose of increasing the area of low strain available for analysis. Forged double cones were sectioned into

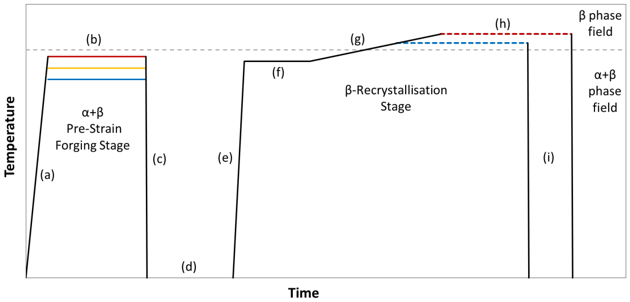

Figure 3: Forging and recrystallisation procedure: (a) heat double cone samples to pre-strain temperature; (b) hold for 90 minutes; (c) forge and water quench; (d) section into 'wedges'; (e) heat wedges to $\alpha + \beta$ temperature; (f) hold for 60 minutes; (g) ramp temperature at 39°C/h to final recrystallisation temperature; (h) water quench or hold at temperature for 60 minutes; (i) water quench.

six 60° 'wedges' used for as-forged analysis and the subsequent β recrystallisation heat treatments.

To accurately represent the industrial process route a 60 minute hold at a temperature high in the $\alpha + \beta$ range preceded a slow 39°C/hour ramp to the final β recrystallisation temperatures of β_{T1} or β_{T2}. Samples were either quenched immediately or held for 30 or 60 minutes with a four extended heat treatments used to investigate further grain coarsening over time. Both forging and heat treatment parameters were chosen as industrially relevant values by TIMET. A summary of the forging and recrystallisation process is outlined in Figure 3.

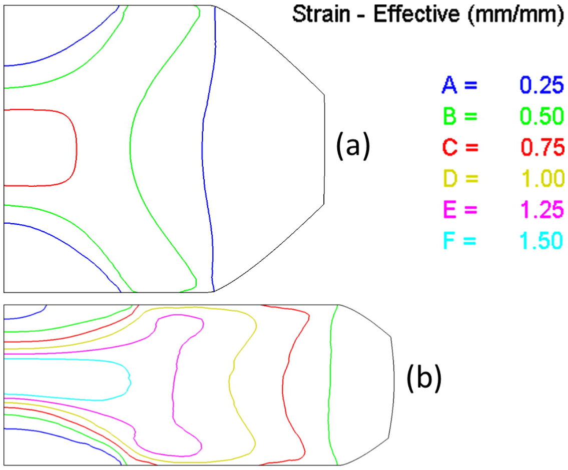

Figure 4: Representative examples of strain profiles produced by DEFORM 2D FE modelling for (a) Ti575 compressed to 50mm final height, and (b) Ti-6Al-4V compressed to 28mm final height. Both examples are for β_{T2}, $4.2s^{-1}$ forgings.

Detailed multi-operation DEFORM 2D modelling of the transfer, rest and forging operations provided a strain profile for each of the forged double cones (Figure 4). Default DEFORM resting and forging heat transfer coefficient were used with approximate shear friction coefficient of 0.25 determined using shape fitting. A parametric study confirmed negligible influence on strain profile from large changes of ±0.1 in friction coefficient. An Alicona Infinite Focus optical microscope was used to map the entire surface of each wedge with the DEFORM strain profile overlain to show regions for analysis. Within these regions the grains size was measured by tracing boundaries and extrapolating their areas (Ti-6Al-4V) or using the Abrams three circle intercept method (Ti575) [9]. Grain size as a function of pre-strain temperature, strain rate, strain, recrystallisation temperature and time at recrystallisation temperature was compared for each alloy with the level of refinement from starting structure also investigated.

Experimental Results

The final β recrystallised microstructures for Ti-6Al-4V and Ti575 alloys exhibited contrasting characteristics. At the time of writing the complete Ti-6Al-4V test matrix has been analysed however only one pre-strain temperature (both deformation rates) has been analysed for Ti575.

Pre-strain temperature, strain rate and strain all had little effect on the final recrystallised microstructure of Ti-6Al-4V with only recrystallisation temperature and time at temperature effecting final grain size. Significantly, the strain distribution had no discernible effect on the distribution of grain sizes throughout any of the recrystallised Ti-6Al-4V wedges. The 'dead-zone' in extended contact with the colder die also fully recrystallised in each wedge further indicating that strain has little effect on the final recrystallised β grain size. Effective strain in these regions ranged from 0.05 to 0.2. Figure 5 presents the β_{T1} immediately quenched and β_{T2} held for 60 minutes recrystallisation tests for the Ti-6Al-4V α/β_{T2} forging at 4.2s^{-1}.

These fully recrystallised microstructures exhibited significant grain growth over time at temperature with no indication imposed strain affected final grain size distribution. This outcome was the primary reason behind the experimental shift to a lower overall deformation with the Ti575 alloy and future tests on Ti-6Al-4V

Pre-strain temperature has yet to be investigated

Figure 5: The Ti-6Al-4V recrystallised microstructure for the α/β_{T2} forging at $4.2s^{-1}$ (a) quenched at β_{T1} and (b) held at β_{T2} for 60 minutes.

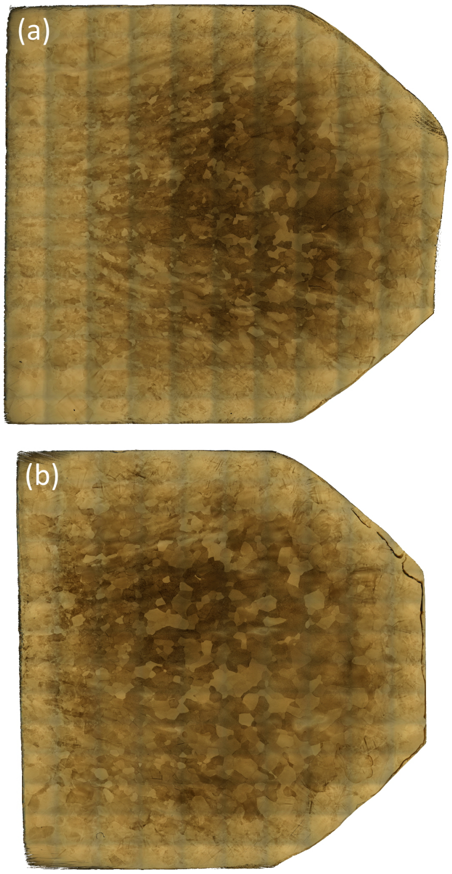

Figure 6: The Ti575 recrystallised microstructure for the $\alpha/\beta_{T2}C$ forging at $4.2s^{-1}$ (a) quenched at β_{T1} and (b) held at β_{T2} for 60 minutes.

for Ti575 however the effect of strain rate and strain is apparent. The equivalent Ti575 micrographs (Figure 6) consistently present increased strain refining the structure and reducing average and maximum grain diameter. Regardless of final β recrystallisation temperature the dead-zone in each Ti575 wedge sample presented a similar grain size to the heat-treated starting material indicating very low strain did not refine the microstructure.

Results and Discussion

Ti-6Al-4V Recrystallisation and Grain Growth

The intention was to use the strain regions generated from DEFORM output to compare grain growth to applied strain however no discernible pattern emerged for this alloy. As shown in the micrographs (Figure 5) the strain regions were largely indistinguishable from each other and no 'cut-off' or gradient was identified where a given strain refined the structure significantly more than another.

The β recrystallisation behaviour of Ti-6Al-4V is presented in Figure 7a and b for β_{T1} and β_{T2} respectively. Data includes all pre-strain temperatures and strain rates and clearly shows grain growth at a rate of approximately 0.4mm per hour for the first hour. It is important to note the time at temperature presented in Figure 7 begins at zero however due to the low temperature ramp rate significant time above the β-transus had elapsed for both tests before this point.

Evident from the graphs is the significance of time above β-transus temperature. The additional time required to reach the higher recrystallisation temperature aligns quite closely with the rate of grain growth shown in Figure 7. One further test completed marginally above the β-transus temperature for 60 minutes presented results that would align with the graph further emphasising final recrystallisation temperature has much less influence than time above the β-transus for the range of temperatures tested.

Of significance to industry and the application of Ti-6Al-4V alloys in structural components is the average and maximum grain diameter at extended heat treatment times. Figure 8 presents the extended time at temperature results for four tests carried out to investigate this response in Ti-6Al-4V. The rate of grain growth slows however it still continues at a rate of 0.15mm per hour to a maximum tested time of 360 minutes.

Large areas of aligned α colonies that may lead to a

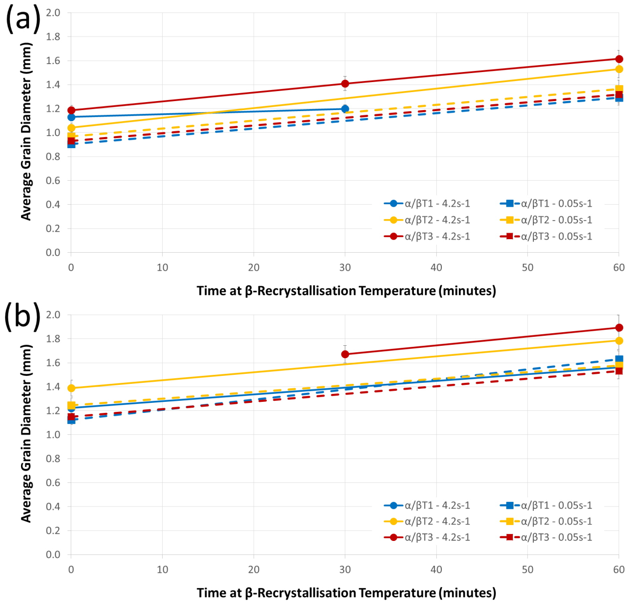

Figure 7: Average Ti-6Al-4V β grain diameter at (a) β_{T1} and (b) β_{T2}.

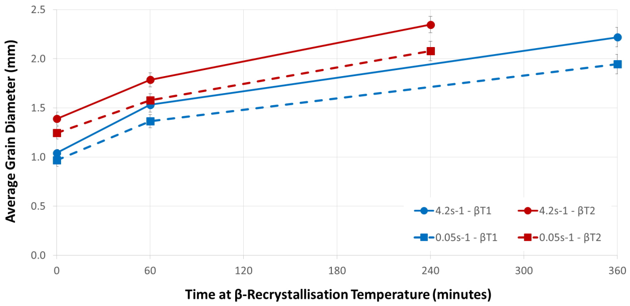

Figure 8: β grain diameter at extended heat treatment times for Ti-6Al-4V.

common orientation being retained throughout $\alpha+\beta$ processing are of principal concern to industry. The maximum β grain diameter is therefore significant as it will likely lead to the largest colonies. Figure 9 presents the evolution of grain diameter over time at recrystallisation temperature for the α/β_{T2} forging at 4.2s^{-1}. The grains coarsen and the curve flattens with extended time at temperature as expected however it does notably produces a single significant outlying grain 7mm in diameter after a 240 minute heat treatment at β_{T2}. The maximum grain diameter from the other three extended heat treatments all produced grains above 5.5mm in diameter with 60 minute heat treatments regularly producing grain diameters above 4mm.

The coarse, inhomogeneous starting structure exhibiting large β grains averaging 2.6 - 5.8mm in diameter and a maximum of 31.8mm was homogenised and refined to an average grain diameter around half that of the starting structure. From these experiments the strain, pre-strain temperature and strain rate has had little effect on the final grain refinement with only time above β-transus temperature influencing the final grain size significantly.

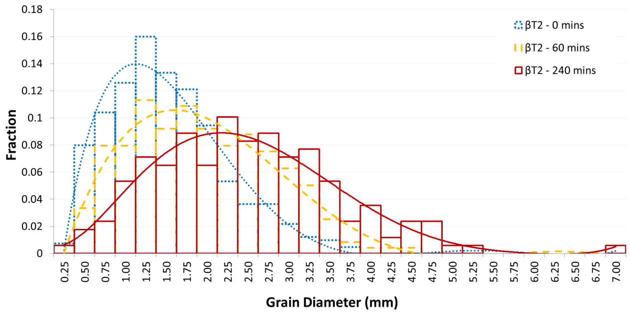

Figure 9: Histogram for Ti-6Al-4V α/β_{T2} forging at $4.2s^{-1}$ showing progressive growth of measured grain size over time.

Ti575 Recrystallisation and Grain Growth

Unlike the Ti-6Al-4V alloy a comparison of final recrystallised grain size versus applied strain was possible. Both average (Figure 10) and maximum grain diameter (Figure 11) reduced with increased strain while the 0.05s^{-1} strain rate (Figure 10a and Figure 11a) resulted in larger grain diameters than the 4.2s^{-1} strain rate (Figure 10b and Figure 11b).

The rate of grain coarsening over time above the β-transus is slower than Ti-6Al-4V at approximately 0.1 - 0.2mm per hour for the first hour. Results of investigation into extended recrystallisation heat treatments and the influence of pre-strain temperature are forthcoming but are hitherto unreported. Similarly identical Ti-6Al-4V tests to 50mm final height will be performed and reported at a later date.

The heat treated starting structure was reduced from a 1.97mm average diameter to under 1.4mm average with both average and maximum reduced further with increased strain.

Conclusions

A study on the β recrystallisation characteristics of Ti-6Al-4V and Ti575 has produced a comprehensive database of final β grain size as a function of $\alpha+\beta$ pre-strain temperature, strain rate, strain, recrys-

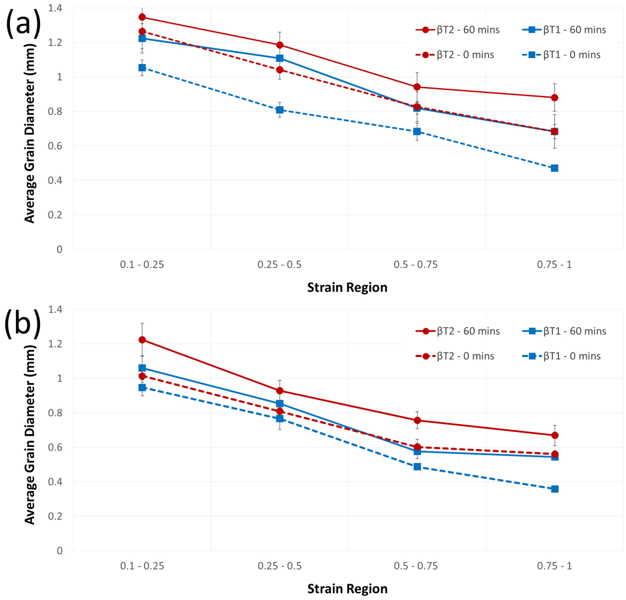

Figure 10: Average Ti575 β grain diameter for α/β_{T2} *forging at (a)* $0.05s^{-1}$ *and (b)* $4.2s^{-1}$*.*

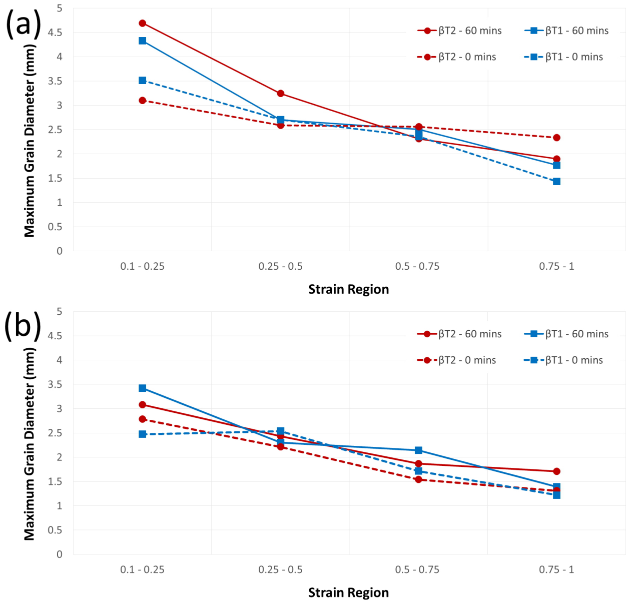

Figure 11: Maximum Ti575 β grain diameter for α/β_{T2} *forging at (a)* $0.05s^{-1}$ *and (b)* $4.2s^{-1}$*.*

tallisation temperature and time at temperature. As input for microstructural models this data can assist in optimising the industrial processing route.

Ti-6Al-4V exhibited a homogeneous β grain structure regardless of imposed strain. Grain growth was consistent at 0.4mm per hour for the first hour and slowed to approximately 0.15mm per hour to a maximum time of 6 hours. A maximum grain diameter of 7mm occurred after a 240 minute heat treatment at β_{T2}.

Ti575 is influenced significantly by imposed strain at the pre-strain stage with average and maximum grain size reducing with increased applied strain. A higher strain rate has shown greater refinement with investigations into pre-strain temperature and extended heat treatments hitherto unreported.

Acknowledgements

The authors would like to acknowledge the AFRC for the use of equipment and TIMET Ltd. for the provision of raw materials and continued support.

References

[1] Hewitt, J. S., Thomas, M. J., Garratt, P., and Bache, M. R. (2014) *Advanced Materials Research* **891-892**, 569–574.

[2] Hewitt, J. S., Davies, P. D., Thomas, M. J., Garratt, P., and Bache, M. R. (2014) *Material Science and Technology* **30**, 1919–1924.

[3] Lütering, G. and Williams, J. C. (2007) Titanium (Engineering Materials and Processes), Springer, 2nd edition.

[4] Ding, R., Guo, Z. X., and Wilson, A. (2002) *Material Science and Engineering* **A327**, 233–245.

[5] Ding, R. and Guo, Z. X. (2004) *Material Science and Engineering* **A365**, 172–179.

[6] Krumphals, A., Stockinger, M., Warchomicka, F., and Sommitsch, C. (2011) In Proceedings of the 12th World Conference on Titanium : pp. 493–496.

[7] Warchomicka, F., Poletti, C., Stockinger, M., and Henke, T. (2010) *International Journal of Materials Forming* **3**, 215–218.

[8] Jackson, M., Dashwood, R. J., Christodoulou, L., and Flower, H. M. (2000) *Material Science and Technology* **16**, 1437–1444.

[9] ASTM E112-13 Standard Test Methods for Determining Average Grain Size ASTM International, West Conshohocken, PA (2013).