Effect of near beta-transus forging parameters on the mechanical and microstructural properties of Ti-6Al-4V – Application to hammer forging

AGIRRE Julen[1,a] *, ERICE Borja[1,2,b], ARRESE Peio[1,c], OTEGI Nagore[1,d] and GALDOS Lander[1,e]

[1]Mechanics and Industrial Production Department, Mondragon Unibertsitatea, Loramendi 4, 20500 Mondragon, Spain

[2]IKERBASQUE, Basque Foundation for Science, 48009 Bilbao, Spain

[a]jagirreb@mondragon.edu, [b]berice@mondragon.edu, [c]peio.arrese@alumni.mondragon.edu, [d]notegi@mondragon.edu, [e]lgaldos@mondragon.edu

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Abstract. Ti-6Al-4V is a widely employed material in the aerospace, power generation and bioengineering industries due to its low density, excellent corrosion resistance and outstanding mechanical properties. Hammer forging is one of the most utilized manufacturing processes to produce high-performance titanium components and it is known that the process parameters highly affect the microstructure, and thus, the mechanical properties of the manufactured parts. Ti-6Al-4V alloy has a temperature dependent dual structure and forging below or above the β-transus transition temperature (≈980ºC) highly influences the resultant microstructure. Due to the significant adiabatic heating in high-speed hammer forging processes the β-transus temperature can be exceeded during the process. Therefore, it is of vital importance to study the phase transformation limits and the resultant effects on the mechanical properties to establish the optimum processing window for the hammer forging of Ti-6Al-4V. In this work, the Direct-Impact Drop Hammer (DIDH), a purpose-built laboratory hammer with a maximum blow speed of 5 m/s is employed to perform intermediate strain rate (≈200 s^{-1}) uniaxial compression tests of Ti-6Al-4V at 900ºC, 940ºC, 980ºC, 1000ºC and 1020ºC. The flow behaviour of this titanium alloy is experimentally characterized under a wide range of hammer forging conditions, and the microstructure of the tested samples is analysed to study the influence of the adiabatic heating on the phase transformation of Ti-6Al-4V.

Introduction

Ti-6Al-4V has become one of the most employed titanium alloys in the aerospace and the biomedical sectors due to its outstanding mechanical properties and relatively low density. The high cost of this alloy is justified in demanding applications as it offers superior performance and good corrosion resistance even under extreme environments [1]. Ti-6Al-4V is a dual α-β structure titanium alloy, and a variety of resulting microstructures can be obtained depending on the processing route and posterior heat treatment employed to obtain the components [2,3]. The final microstructure highly influences the mechanical properties of the manufactured part; therefore, it is of vital importance to analyse the influence of temperature on the phase transformation of this titanium alloy to correctly define the process parameters

Hammer forging is one of the most employed manufacturing processes for Ti-6Al-4V components, as it is versatile and very cost-effective for large series production [4]. The forging temperature range for this titanium allow is however, narrow, and in general two forging strategies are differentiated in function of the processing temperature [1]. On the one hand,

α-β forging, when forging is carried out below the β-transus temperature (≈980ºC); and on the other hand, β forging, if the forging temperature is above β-transus [5]. Due to the high adiabatic heating found in hammer forging attributed to the high strain rates reached in the process (≈200 s^{-1}), the temperature in some zones of the forged component can exceed the β-transus critical temperature [6]. This can result in undesired resulting microstructures, and hence, poor mechanical properties in the manufactured part.

Therefore, the narrow processing temperature range of Ti-6Al-4V and the complexity of hammer forging itself, makes essential the use of finite element (FE) numerical simulations to explore diverse forging strategies and determine optimised process parameters [4]. It is well-known however that the correctness of the simulation results is directly linked to the accuracy of input parameters and boundary conditions. The correct definition of the material behaviour under the process conditions is one of the most important input parameters, and experimental testing is generally needed for that purpose. Experimental data is employed to calibrate the material models that numerically represent critical aspects, such as the flow behaviour and the microstructural evolution of the material in function of the processing strategy.

Experimental material characterization at the intermediate strain rate range found typically in hammer forging processes (10^2-10^3 s^{-1}) is however challenging, and consequently, the flow behavior and phase transformation of Ti-6Al-4V under these conditions is rarely reported in the literature. The use of universal testing machines equipped with conventional load cells becomes extremely challenging for testing at this strain rate range since they often have a limited stroke velocity. If such velocity is not an issue, then inertia effects and wave propagation become more relevant making the load measurements more troublesome [7]. The most used equipment for dynamic testing is the well-known Split Hopkinson Pressure Bar (SHPB) system, but it also has certain limitations when it comes to testing at these strain rates [7]. As an alternative to the SHPB systems for intermediate strain rate testing, we developed an in-house designed and constructed laboratory facility: the Direct-Impact Drop Hammer (DIDH). In this work, this purpose built machine was employed for the experimental characterisation of Ti-6Al-4V under hammer forging conditions.

The Direct-Impact Drop Hammer (DIDH)

Considering the difficulties to perform intermediate strain rate tests employing universal hydraulic commercial testing devices and SHPB systems, an automatized in-house Automatic ThermoMechanical Tester (ATMT) was designed and constructed. This testing machine is capable of reproducing a wide range of hot and cold industrial metal forming conditions, from low strain rates (<1 s^{-1}) up to intermediate strain rates (>100 s^{-1}). This novel apparatus (Fig. 1a) was designed to be able to test diverse forming strategies, including intermediate heating cycles combined with different loading rate scenarios. The ATMT is composed of four main sections: a heating furnace (max. 1350ºC), an isothermal hydraulic press for low strain rate tests (<1 s^{-1} and max. 1350ºC), a cooling system, and the main novelty, the Direct-Impact Drop Hammer for intermediate strain rate testing. To reduce human errors as much as possible and increase the repeatability of the tests, the apparatus is fully automatized and the sample manipulation is carried out by an electro-pneumatic arm that is integrated in the machine.

Focusing on the DIDH, its mechanical module is comprised of a 92 kg hammer that is pushed by a high-pressure pneumatic cylinder propelling it towards the anvil, the fixed part of the system. The hammer can be set-up at different heights, which allows for impact velocities to range from 2.5 to 5 m/s and a maximum applicable deformation energy of 1.15 kJ. Regarding data acquisition, the anvil is instrumented with a piezoelectric force sensor allowing for direct force measurements. The kinematics of the tests are recorded with a high-speed camera (Fig. 1b) and post-processed by Digital Image Correlation (DIC). The suitability of the DIDH for the mechanical characterisation within this strain rate regime was successfully demonstrated [8]. Interestingly, this device

incorporates an optimized cooling system which is capable of quenching the tested sample in less than 1 s after the high-speed test takes place. This is of particular interest for the microstructural evolution characterisation of materials combining both high temperatures and intermediate strain rate tests.
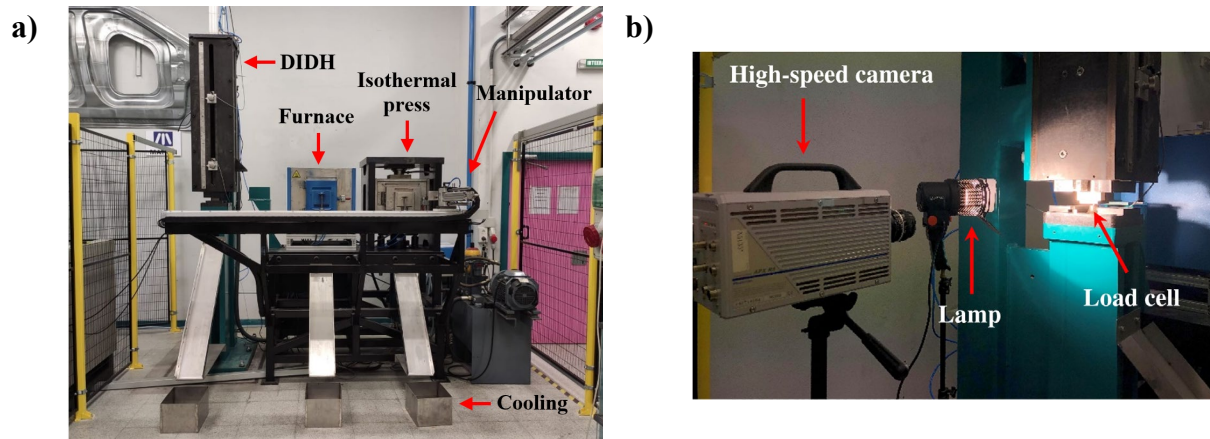

Fig. 1. a) The Automatic ThermoMechanical Tester (ATMT) and b) the data acquisition setup in the DIDH.

Experimental Procedure

In this work, the new DIDH was employed to characterise the flow behaviour of Ti-6Al-4V alloy under hammer forging conditions. Uniaxial compression tests were performed at 900 ºC, 940ºC, 980ºC, 1000ºC and 1020ºC using Ø16x24 mm cylindrical samples and they were air cooled after the compression. A deformation speed of 5 m/s was employed in all the cases, which means that a deformation energy of 1.15 kJ was applied to the samples. These were painted with the CONDAERO 313 glass coating to protect the surface from oxidation and reduce the friction between the sample and the tools.

To monitor the hammer kinematics, a Photron Fastcam-APX RS250K high-speed camera with appropriate illumination lamps was utilised. It was set up to record at 15,000 fps with a resolution of 256 x 512 px^2. The specimen length history $l[t]$ was obtained by DIC analysis from the displacement history of the hammer, which was calculated by post-processing the high speed camera images with the GOM Correlate software [9]. To obtain the force histories $F[t]$, a Kistler 9106A piezoelectric force sensor mounted directly on the anvil was employed in combination with a Tektronix TSD 2004B oscilloscope with an acquisition frequency of 300 kHz. As the displacement of the DIDH tests was recorded with a lower acquisition frequency, the displacement histories were linearly interpolated for the load cell time base.

The axial true stress (σ), true strain (ε) and true strain rate ($\dot{\varepsilon}$) were calculated by $\sigma = F[t]/A[t]$, $\varepsilon = \ln(h[t]/h_0)$, and $\dot{\varepsilon} = v[t]/h[t]$, respectively, where $F[t]$ is the force measured by the piezoelectric force sensor, h_0 is the initial sample height, $h[t]$ and $A[t]$ are the instantaneous height and cross-section area of the sample, respectively, and $v[t]$ is the instantaneous tool velocity, assuming $[0] = 0$ s^{-1}.

Results and Discussion

The same blow speed (5 m/s), and hence, the same deformation energy (1.15 kJ) was employed in all the tests, therefore, as the strength of the Ti-6Al-4V decreases with increasing the forming temperature, higher deformations were obtained at higher temperatures (
Fig. **2**). Final true strains of 0.63, 0.77, 1.01, 1.12 and 1.15 were reached in the tests performed at 900ºC, 940ºC 980ºC, 1000ºC and 1020ºC, respectively. Three repetitions were performed per condition showing very little deviation between them, with a mean stress deviation of 1.29 % in the worst case. This is mainly because the tests are performed automatically in the DIDH.

Fig. 2. Initial sample and samples tested in the DIDH at 900ºC, 940ºC, 980ºC, 1000ºC and 1020ºC (from left to right).

A friction factor (*m*) of 0.3 was estimated by inverse simulation taking into account the barrelling of the tested samples (Fig. 2). FORGE® simulation software was employed for that purpose. The estimated friction factor is in accordance with the friction reported by Zhu et al. [10] for Ti-6Al-4V alloy forgings using glass lubricant.

Force-displacement curves of the intermediate strain rate tests performed in the DIDH at 900ºC, 940 ºC, 980ºC, 1000ºC and 1020ºC are presented in Fig. 3. The high-speed blow of the DIDH lead to some oscillations in the force readings particularly at the beginning of the curves. However, these fade out to certain extent as tests progress leaving the piezoelectric load cell noise as the only source of the oscillations, and the material behavior is clearly identified.
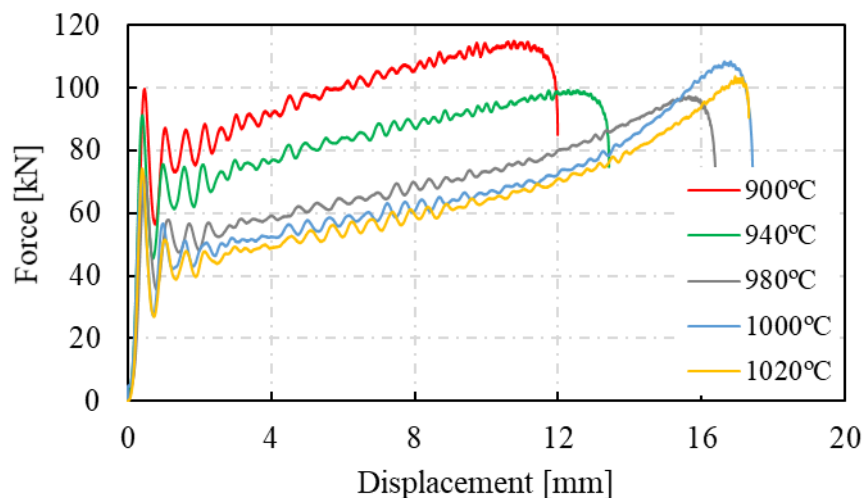

Fig. 3. Force-displacement curves of tests performed in the DIDH with a blow speed of 5 m/s at 900ºC, 940ºC, 980ºC, 1000ºC and 1020ºC.

The true stress-strain curves are shown in Fig. 4. A clear and coherent temperature dependency is observed in the results, with lower forces at higher temperatures. The softening observed in the curves can be attributed to the considerable adiabatic heating and low heat dissipation times found at these strain rates. No analytical adiabatic heating correction was applied to the flow curves

presented in Fig. 4. The true strain rate evolution is also presented in Fig. 5, in which the intermediate strain rates reached in the tests demonstrate that the DIDH is capable of testing at strain rates comparable to those found in industrial hammer forging operations. This results are of significant industrial and scientific relevance as few laboratory thermomechanical testers allow testing at both intermediate strain rates and high temperatures. Therefore, the study of the flow behavior of Ti-6Al-4V under hammer forging conditions is hardly reported in the literature.
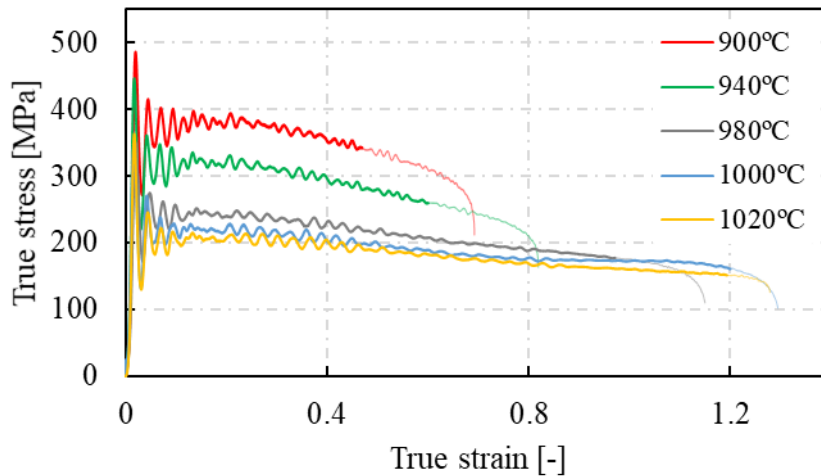
Fig. 4. True stress-true strain curves of Ti-6Al-4V tested in the DIDH at intermediate strain rates ($\approx 200\ s^{-1}$).

A non-constant strain rate evolution is observed in Fig. 5, which occurs due to the nature of the DIDH tests. The hammer velocity starts decreasing once it gets into contact with the sample until it completely stops. Anyhow, due to the optimised sample dimension a relatively constant strain rate evolution is attained up to high strain levels, especially at higher temperatures. As a reference, thicker solid line are depicted in Fig. 4 and Fig. 5 until the strain rate dropped below 80 % of the initial strain rate value.
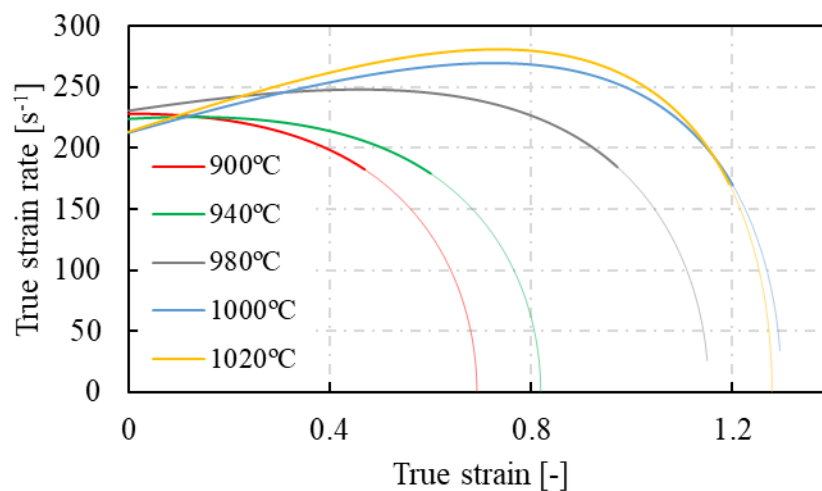

Fig. 5. True strain rate evolution of the DIDH tests at intermediate strain rates.

The effect of this strain rate drop in the flow curves is irrelevant, as the initial and the final strain rates are in the same order of magnitude. Mean strain rates attained up to this point for the

tests at 900ºC, 940ºC, 980ºC, 1000ºC and 1020ºC are 215 s^{-1}, 215 s^{-1}, 235 s^{-1}, 245 s^{-1} and 250 s^{-1}, respectively. At higher strain levels beyond the 80 % strain rate drop, the strain rate decreases considerably and the rate effect becomes more significant in the flow curves, with a sharp drop at the end of the curves (Fig. 5).

The strain rate dependency of Ti-6Al-4V is clearly observed in the comparison between the low strain rate (<10 s^{-1}) flow curves at 900ºC presented by Porntadawit et al. [11] and the intermediate strain rate (215 s^{-1}) flow curve obtained from the test in the DIDH at the same temperature (Fig. 6). A classical strain rate dependency is shown, with higher flow stresses at higher strain rates.
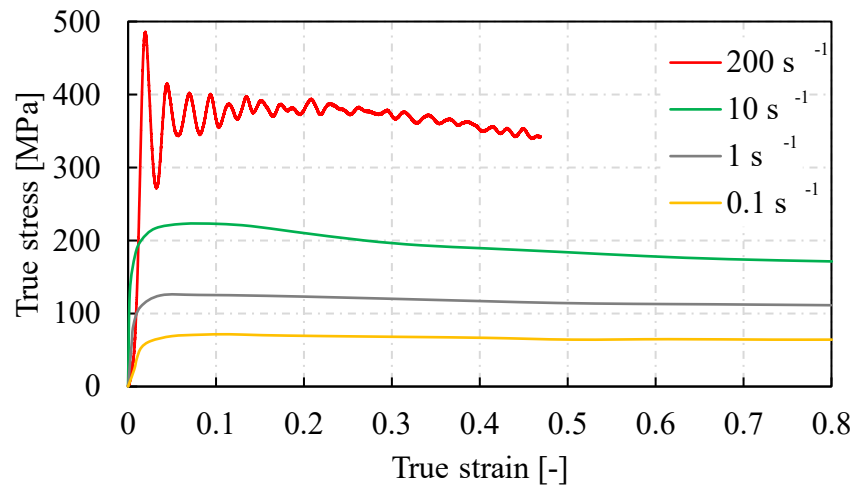

Fig. 6. Comparison between low strain rate (0.1 s^{-1}, 1 s^{-1} and 10 s^{-1}) flow curves of Ti-6Al-4V at 900 ºC extracted from [11] and the intermediate strain rate flow curve obtained from the DIDH test at the same temperature.

Once the tests were performed, the tested samples were cut from the cross-section to analyse the resulting microstructure (Fig. 7). Samples were prepared for microstructural analysis by conventional sanding and polishing procedures and they were etched with Kroll's reagent.
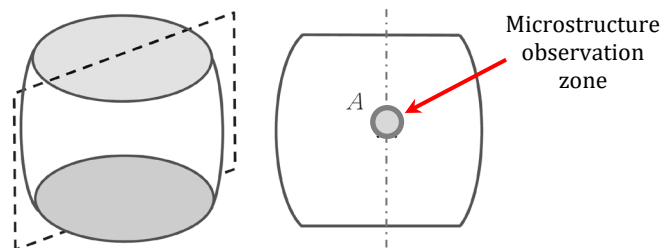

Fig. 7. Cutting plane of the tested samples to analyse the resulting microstructure.

Fig. 8 shows the micrographs of the samples tested in the DIDH at intermediate strain rates (≈200 s^{-1}) at temperatures of 900ºC, 940ºC, 980ºC, 1000ºC and 1020ºC. A clear bimodal microstructure composed of equiaxed α phase and lamellar α-β is found at the tests performed at 900ºC and 940ºC, with lower equiaxed α fractions with higher temperatures. Samples tested at 980ºC and 1000ºC, close to the β-transus transition temperature, show even lower equiaxed α fractions, and the sample tested at 1020ºC show a clear β microstructure.
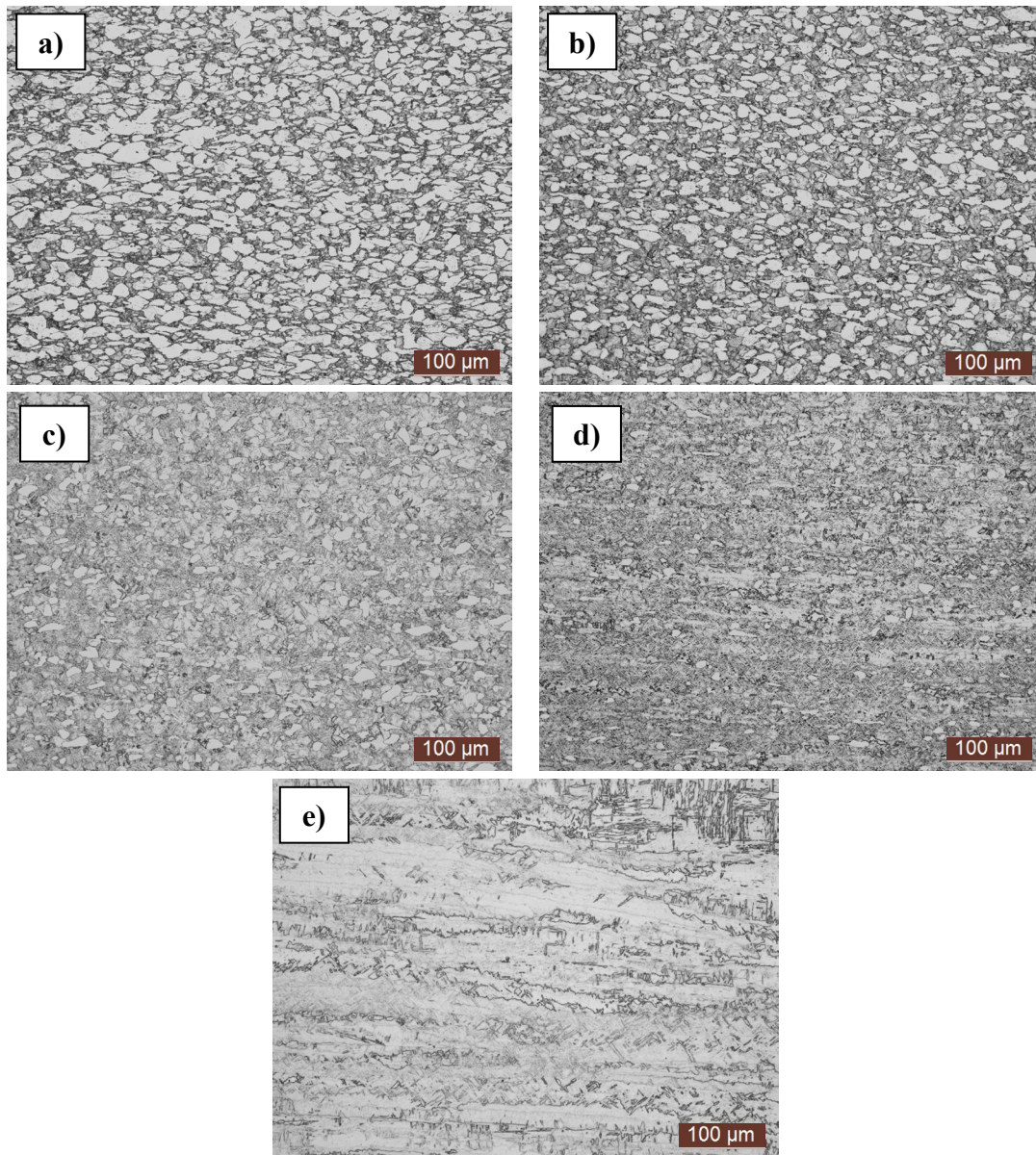
Fig. 8. Micrographs of the samples tested in the DIDH at intermediate strain rates at a) 900ºC, b) 940ºC, c) 980ºC, d) 1000ºC and e) 1020ºC.

Summary

The following conclusions were extracted from the present work:

- The purpose-built laboratory hammer, the Direct-Impact Drop Hammer (DIDH), is a suitable thermomechanical tester for testing under both intermediate strain rates and high temperatures. As the tests are performed automatically, the results show a great repeatability.
- The flow behaviour of Ti-6Al-4V was successfully characterised under a wide variety of hammer forging conditions. A clear temperature dependency was observed in the tests perform from 900ºC to 980ºC. This dependency decreased significantly in the tests performed from 980ºC to 1020ºC, close and beyond the β-transus transition temperature.
- A clear bimodal microstructure was found in the tests performed below the β-transus temperature, at 900ºC and 940ºC, with a lower equiaxed α phase fraction at higher temperatures. Even lower α fractions were observed at the tests performed at 980ºC and

1000ºC, close to the β-transus temperature, and only β-phase microstructure was observed in the tests performed at 1020ºC.

Acknowledgments

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