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THE KINETICS OF PHASE TRANSFORMATIONS DURING CONTINUOUS COOLING OF THE Ti6Al4V ALLOY FROM THE SINGLE-PHASE β RANGE

KINETYKA PRZEMIAN FAZOWYCH PRZY CHŁODZENIU CIĄGŁYM STOPU Ti6Al4V Z ZAKRESU JEDNOFAZOWEGO β

The paper reports on a study of the kinetics of phase transformations during continuous cooling of the alpha-beta Ti6Al4V titanium alloy from the β range. After cooling from 1020°C at a rate higher than critical the martensitic $\beta \rightarrow \alpha$' transformation occurred. At rates lower than critical in addition to the martensitic reaction also the diffusional $\beta \rightarrow \alpha$ transformation took place. Metallographic examination of samples cooled at various rates within the range of diffusional transformations, revealed variations in the α phase morphology changing from lamellar, after cooling at between 7.3 and 0.015°C/s, to granular, as observed after cooling at 0.012°C/s. The phase transformations were also clearly seen in dilatometric curves.

Keywords: phase transformations, microstructure, hardness, dilatometric curve, CCT diagram

W artykule dokonano oceny kinetyki przemian fazowych przy chłodzeniu ciągłym dwufazowego stopu tytanu Ti6Al4V za pomocą wykresu CTPc wykonanego dla temperatury 1020°C (z zakresu jednofazowego β). Po chłodzeniu stopu od temperatury 1020°C z szybkością większą od krytycznej odnotowano wystąpienie przemiany martenzytycznej $\beta \rightarrow \alpha$'. Zastosowanie szybkości chłodzenia mniejszej od krytycznej powoduje, że obok tej przemiany występuje również przemiana dyfuzyjna $\beta \rightarrow \alpha$. Obserwacje metalograficzne stopu Ti6Al4V, chłodzonego z różnymi szybkościami w zakresie przemian dyfuzyjnych, pozwalają zauważyć wyraźne zmiany w morfologii fazy α. Przy chłodzeniu z szybkościami w zakresie 7,3 ÷ 0,015°C/s wydzielenia tej fazy mają charakter płytkowy, zaś przy najmniejszej zastosowanej szybkości (0,012°C/s) zaobserwowano wydzielenia tej fazy w formie ziarnistej. Potwierdzeniem przemian fazowych zachodzących podczas chłodzenia stopu są zarówno zmiany zachodzące w mikrostrukturze, jak i efekty dylatacyjne obserwowane na dylatogramach podczas chłodzenia.

1. Introduction

The fast development of modern materials consists in searching for new alloys and improving the already existing ones in order to meet the end-users requirements. Titanium alloys are currently among the most attractive materials since they are characterised by an excellent combination of high specific strength (tensile strength/density), high temperature creep resistance and corrosion resistance. Therefore they are increasingly used in the chemical industry, electronics, aircraft and shipbuilding, processing of food and paper, production of medical and sport equipment, as well as for components of steam turbines, jet engines, cars and rackets [1÷5]. Titanium alloys are paramagnetic which makes them useful for construction of modern submarines which are difficult to detect by magnetic methods. Due to their relatively good biocompatibility titanium alloys are widely applied for knee and hip replacements and in dentistry [6].

A typical representative of alpha-beta titanium alloys is the Ti6Al4V grade, which is malleable and can be heat treated to a broad range of microstructure and mechanical properties. However, among the so far performed and presented investigations [4, 5, 7÷10], there is lack of a comprehensive, qualitative and quantitative assessment of the kinetics of phase transformations occurring in the Ti6Al4V alloy and its influence on mechanical properties. In the case of alpha-beta titanium alloys, the knowledge of the phase transformation kinetics during continuous cooling from both the $\alpha+\beta$ range and β range is essential if the material is to be properly processed. Therefore the main objective of this paper is to study the kinetics of phase transformations occurring during continuous cooling of the Ti6Al4V alloy from the β range (1020°C) and to establish a CCT diagram which will

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facilitate its continuous tempering (aging). In the future it is planned to study the kinetics of phase transformations taking place during heating from the as-quenched condition in order to draw a CHT (Continuous Heating Transformation) diagram which will additionally assist in alloy processing to the required microstructure and properties, as experienced with ferrous alloys [11].

2. Experimental procedure

The Ti6Al4V alloy used in this investigation was delivered in the form of ø35 mm × 250 mm bar in as-annealed condition. The heat treatment consisted of heating to 750°C, holding for 2 hours at 750°C, furnace cooling to 600°C, holding for 2 hours at 600°C and finally cooling to room temperature in air.

Its chemical composition is given in Table 1.

TABLE 1
Chemical composition of the Ti6Al4V alloy

Chemical composition, wt.%							
Al	V	Fe	C	O_2	N_2	H_2	Ti
6.5	4.4	0.15	0.023	0.130	0.017	0.0024	bal.

Cylindrical samples ø4 mm × 25 mm were cut out from the longitudinal section of the bar and applied for phase transformation studies using an optical LS4 dilatometer. As a result the CCT diagram was drawn for cooling from 1020°C, i.e. 50°C above the β-transus temperature. The temperature selection was verified by both microstructural analysis of samples heated to various temperatures between 700 and 1250°C, held for 60 minutes and water quenched, as well as by dilatometry.

To study the kinetics of phase transformations during continuous cooling, the samples were heated at 3°C/min. to 1020°C, held for 20 minutes, and cooled to room temperature at rates ranging from 23.1 to 0.012°C/s. Variations in the sample length (ΔL) with temperature were recorded and analysed in order to estimate the start and finish temperatures of phase transformations. The whole set of cooling curves was used to draw the CCT diagrams.

Samples representing all cooling rates were subsequently mounted in duracryl, ground on a wheel grinder and then on water-lubricated abrasive papers of gradually decreasing SiC grit size, and polished using an alumina suspension. The cross sections were pre-etched in 6% HF and finally etched in a solution: 2 ml HF + 2 ml HNO_3 + 96 ml H_2O. Thus prepared metallographic samples were tested for hardness and subjected to microstructural observations by an optical ZEISS AXIOVERT 200 MAT microscope.

The hardness tests were carried out by means of a HPO250 type Vickers apparatus under a load of 98 N. The Vickers hardness numbers are included in the CCT diagram.

3. Results and discussion

As shown in Figure 1, the microstructure of the Ti6Al4V alloy heated to 970°C and water quenched consists of oriented, acicular precipitates of α' phase which have been formed as a result of a diffusionless transformation. The bright grains of α phase are not seen which indicates that α is absent after 1-hour hold at 970°C. The as-quenched hardness is 385 HV.

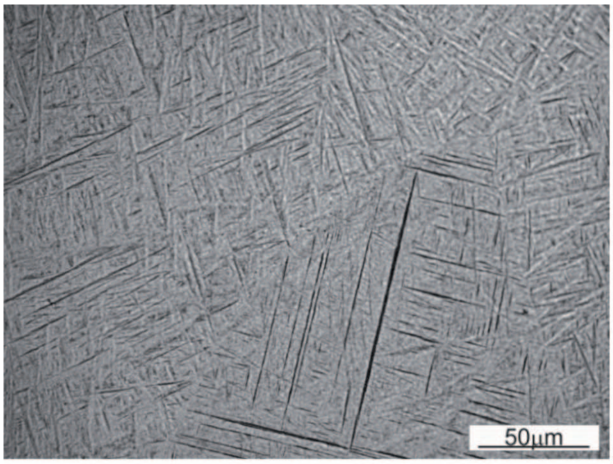

Fig. 1. Microstructure of the Ti6Al4V alloy annealed for 60 minutes at 970°C and water quenched

Figure 2 shows dilatometric curves of samples cooled from 1020^{o}C to room temperature at various rates.

At low cooling rates ($\leqslant$7.3°C/s) the diffusional $\beta \rightarrow \alpha$ transformation start ($T^s_{\beta\rightarrow\alpha}$) and finish ($T^f_{\beta\rightarrow\alpha}$) temperatures manifest themselves as a marked decrease and increase of the sample length, respectively (Figs. 2a-2c) and the decreased solubility of alloying elements in β induces precipitation of α. By increasing the cooling rate to 23.1°C/s it is possible to record dilatometric effects from the martensite reaction (Fig. 2d) and observe acicular α' precipitates in the alloy microstructure.

In order to plot the CCT diagram presented in Figure 3 eight various cooling rates, from 23.1°C/s (corresponding to quenching in icy water) to 0.012°C/s, were applied. The diffusionless $\beta \rightarrow \alpha$' transformation occurred during cooling at 23.1°C/s although the complete transformation of β into α' had been reported to take place in the Ti6Al3Mo, Ti6Al3Mo1V and Ti6Al2Mo2Cr alloys after cooling at minimum 40°C/s [1, 3, 7, 8]. For alloy containing 5.8% Al, 4.19% V, 0.03% C, 0.033% N, 0.20% O and 0.08% Fe the M_s and M_f temperatures are 915 and 690°C, respectively [8], whereas the critical cooling rate from 1025°C has been estimated at ~9.5°C/s (dashed line in the CCT diagram).

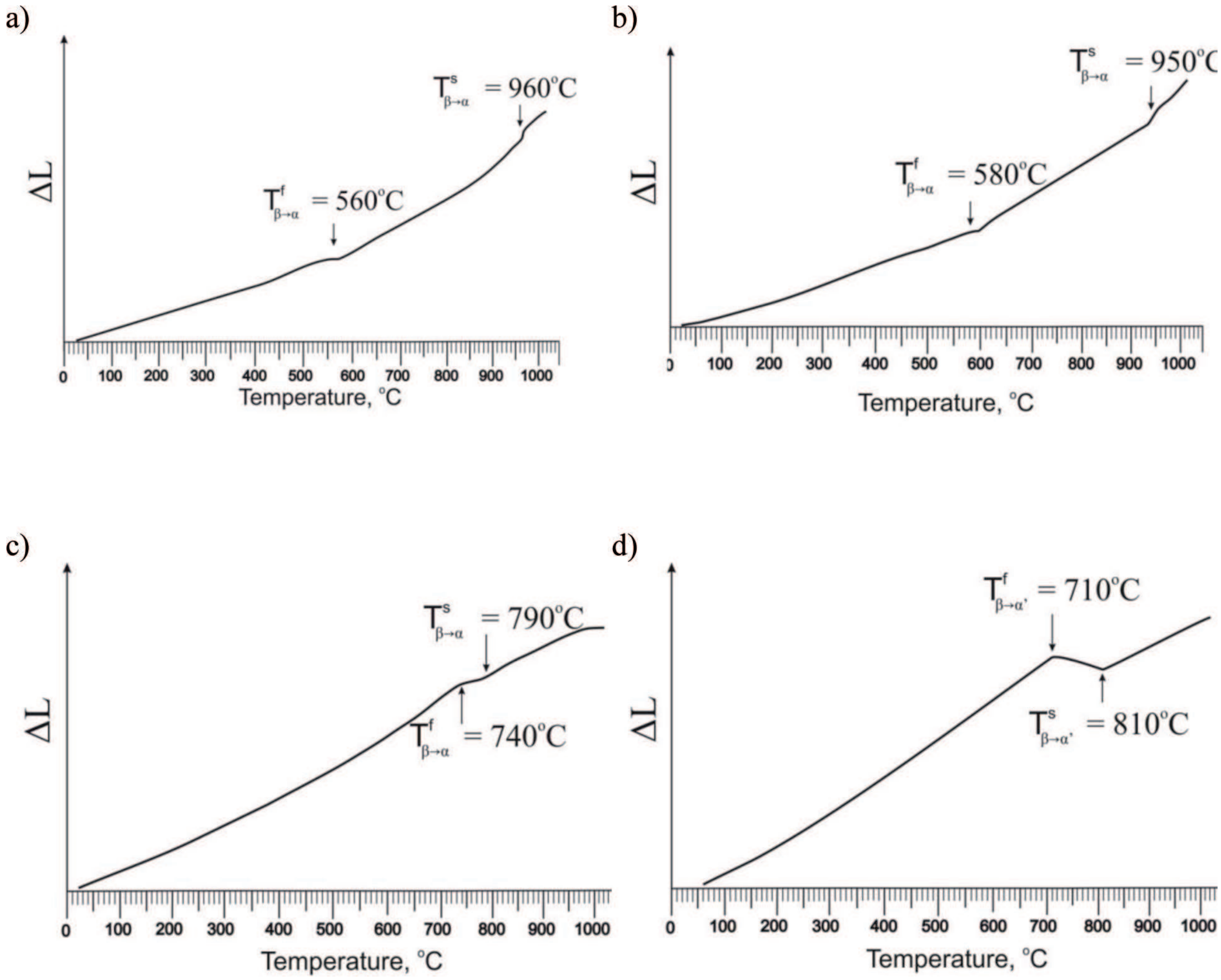

Fig. 2. Dilatometric curves of the Ti6Al4V alloy cooled from 1020°C at: 0.012°C/s (a), 0.030°C/s (b), 7.3°C/s (c) and 23.1°C/s (d)

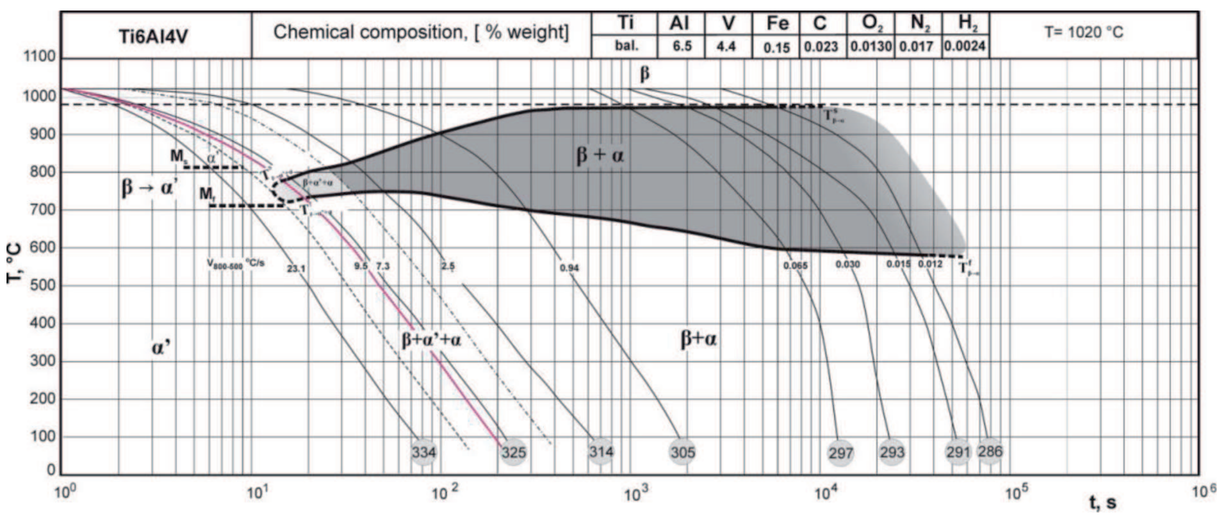

Fig. 3. The CCT diagram for the experimental Ti6Al4V alloy

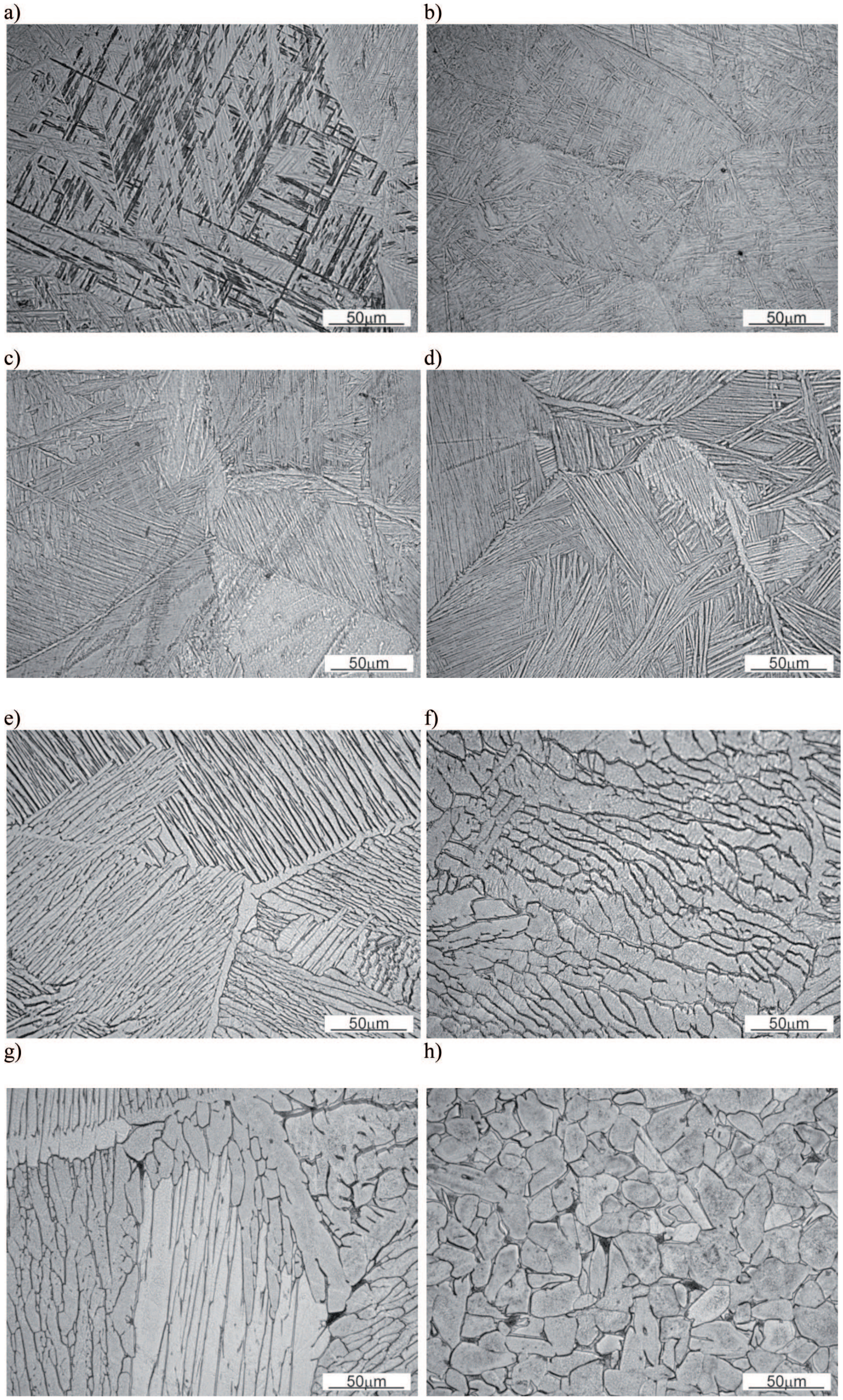

Fig. 4. Optical micrographs of the Ti6Al4V alloy cooled from 1020°C at: 23.1°C/s (a), 7.3°C/s (b), 2.5°C/s (c), 0.94°C/s (d), 0.065°C/s (e), 0.030°C/s (f), 0.015°C/s (g) and 0.012°C/s (h)

During cooling at 7.3°C/s the martensitic $\beta \rightarrow \alpha$' reaction coincides with the diffusional $\beta \rightarrow \alpha$ transformation. The M_s and M_f temperatures were not marked in the CCT diagram for this cooling rate since the sample elongation related to the martensitic reaction was not recorded although precipitates of α' were revealed in the microstructure as seen in Fig. 4a. Therefore between the dashed and dashed-dotted lines in the CCT diagram the transformation start and finish temperatures were marked as $T^s_{\beta\rightarrow\alpha'+\alpha}$ and $T^f_{\beta\rightarrow\alpha'+\alpha}$, respectively. Beyond the dashed-dotted line, for cooling rates lower than 2.5^{o}C/s, only the diffusional $\beta \rightarrow \alpha$ transformation took place.

The microstructures of all samples used to prepare the CCT diagram are presented in Figure 4. By decreasing the cooling rate from 23.1 to 7.3°C/s it was possible to causes significant changes in the microstructure of the investigated alloy (Fig. 4a, b). Although a clear dilatometric effect related to the martensitic reaction was not recorded for cooling at 7.3°C/s optical examination of the sample microstructure (Fig. 4b) revealed scarce α' phase inclusions among lamellar α Widmannstatten precipitates. This is consistent with the data published elsewhere [7, 8] for cooling at rates >5°C/s.

At 2.5°C/s the oriented α plates precipitate to grow as Widmannstatten colonies from the prior β grain boundaries towards the grain centre but α also occurs as a grain boundary film (Fig. 4c). Further decrease in the cooling rate to 0.94÷0.065°C/s results in broadening the α lamellas (Fig. 4d e). While cooling at 0.030°C/s (Fig. 4f) or slower (Fig. 4g) the appearance of α precipitates changes from lamellar to granular which is accompanied by grain growth (Fig. 4h).

4. Conclusions

The following conclusions can be drawn from the obtained results:

1. Martensitic transformation occurred in the alpha-beta Ti6Al4V alloy cooled from the β phase range (1020°C) at 23.1°C/s. After cooling at 7.3°C/s both dispersed α and α' martensite were present in the alloy, whereas during cooling at 2.5°C/s or slower only diffusional transformation took place resulting in entirely α structure.
2. The α phase morphology was strongly affected by the cooling rate and appeared as Widmannstatten lamellas (7.3÷0.065°C/s) or equiaxed grains (0.015÷0.012°C/s).
3. Decreased cooling rate increased the lamella/grain size.
4. Decreased cooling rate (from 23.1 to 0.012°C/s) decreased the hardness of the Ti6Al4V alloy (from 334 to 286 HV).

Some ideas for future work arise from this investigation and, from the viewpoint of alloy heat treatment (tempering/aging), it will be instrumental to construct an analogous CHT diagram for heating from as-quenched condition.

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