Arch. Metall. Mater., Vol. 61 (2016), No 2B, p. 1115–1120

DOI: 10.1515/amm-2016-0187

M. WOJTASZEK*#, T. ŚLEBODA*, G. KORPAŁA**

HOT PROCESSING OF CAST AND PM Ti-6Al-4V ALLOY

Quantitative and qualitative evaluation of the influence of the applied sample morphology as well as parameters of deformation on the microstructure and selected properties of Ti-6Al-4V alloy after deformation was presented. Both cast Ti-6Al-4V alloy and powder compacts were used as the material under investigation. P/M preform was produced from the mixture of elemental powders, by hot compaction. The samples of compacts as well as cast alloy were subjected to plastometric tests under various conditions. The influence of the state of the investigated Ti-6Al-4V alloy on the character of flow curves was determined. The microstructure and hardness after deformation were evaluated and compared. Basing on the results of plastometric tests, the suitable thermo-mechanical parameters of forging of Ti-6Al-4V alloy were determined. The charge was machined from the compacts and from cast material, and both types of forging stock were hot-forged. The microstructure as well as hardness of the forgings were compared.

Keywords: titanium alloy, hot compaction, hot forging, thermo-mechanical parameters, microstructure, properties

1. Introduction

Titanium and its alloys find their applications mainly in aircraft, automotive and shipbuilding industries, as well as in medicine [1-4]. The advantages of titanium alloys include low specific gravity, high strength, crack resistance, fatigue strength and corrosion resistance. The stability of its properties under dynamic load conditions is also important [5]. The disadvantages of titanium and its alloys include low heat conduction, troublesome processing [6-9] and high cost of machining [10]. The most commonly used titanium alloy is Ti-6Al-4V. This alloy also shows heat resistance, weldability and workability. The last feature mentioned means that this alloy can be subjected to forming with application of plastic working processes [11]. The most commonly used form of a material is a casting, while the alternative is the application of semi-finished products manufactured by means of powder metallurgy. When forming products of titanium alloys by means of powder metallurgy, different processes can be employed, such as hot pressing and sintering, isostatic pressing and others [1,8,12-15]. This allows to obtain final products or semi-finished products for further processing, mainly in extrusion or forging processes [16], which results in many advantages. The plastic working makes it possible to extend the products shape range by including long or complex-shape products. The possibility to control the process conditions allows to control the phase composition and grain size. The process can be realized using the processing lines for forming the cast stock, without their modification [17]. Therefore, this technology may result in improving the properties and reducing the production costs of Ti-6Al-4V alloy products, especially by applying relatively inexpensive mixtures of elemental powders and elimination of machining. The possible effect may be the extended use of the alloy in more commonly available applications.

2. Material under investigation and research methods

The initial materials to be used in the investigations and forging tests were cast Ti-6Al-4V alloy as well as P/M compact obtained by hot sintering of the mixture of elemental powders. The specimens of 8 mm diameter and 14 mm height of both materials were prepared. The temperature and strain rate ranges suitable for Ti-6Al-4V alloy were determined and the schedule of plastometric tests was prepared. The tests were performed at Institut für Metallformung, TU-Freiberg, Germany, with application of BÄHR WUMSI hydraulic simulator. The plastometric tests were scheduled considering the possible use of the results to describe the material behaviour when forging in industrial conditions. Therefore, the limitations resulting from temperature and strain rate ranges possible to achieve in forging shops were taken into account. The specimens were heated in the furnace to the temperature of 1000°C, held at this temperature for 10 minutes, then cooled down to the test temperature and deformed at a specified strain rate. The deformation was realized at strain rates of 1, 10 and 20 s^{-1}, at the temperatures of 850, 900 and 950°C. The specimens were cooled in the air. Basing on the

* AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, FACULTY OF METALS ENGINEERING AND INDUSTRIAL COMPUTER SCIENCE, 30 A. MICKIEWICZA AL., 30-059 KRAKOW, POLAND
** TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG, INSTITUT FÜR METALLFORMUNG, 4 BERNHARD-VON-COTTA STR., 09-599 FREIBERG, GERMANY

Corresponding author: mwojtasz@metal.agh.edu.pl

results of plastometric tests, the favourable parameters of die forging process were determined and then verified in industrial conditions. The forging process was realized using a crank press in HSW – Zakłady Kuźnia Matrycowa Ltd. in Stalowa Wola, Poland. The cylindrical stock of 50 mm diameter and 26 mm height was selected and prepared from both cast material and P/M compacts. The forging process was performed applying the same schedule as that used in plastometric tests. The stock was heated to the temperature of 1000°C, held at this temperature for 10 minutes, then cooled down in the air to the temperature of 900°C. The temperature was controlled inside the stock (pin-hole with thermocouple) as well as on the surface (pyrometer). Then, the stock was placed in the dies heated to approximately 300°C and forged in two stages – in roughing impression and in finishing impression. After forming, the forgings were taken out of the die and cooled in the air.

For the specimens after upsetting, metallographic specimens were prepared in the plane parallel to the axis and passing through the centre. Metallographic examinations of specimens in the initial state, in the state after upsetting and after forging were performed by means of light microscopy using Leica DM4000M microscope. Hardness measurements were made using Vickers method. Five measurements for each specimen were performed, with application of Zwick NOLAN hardness tester.

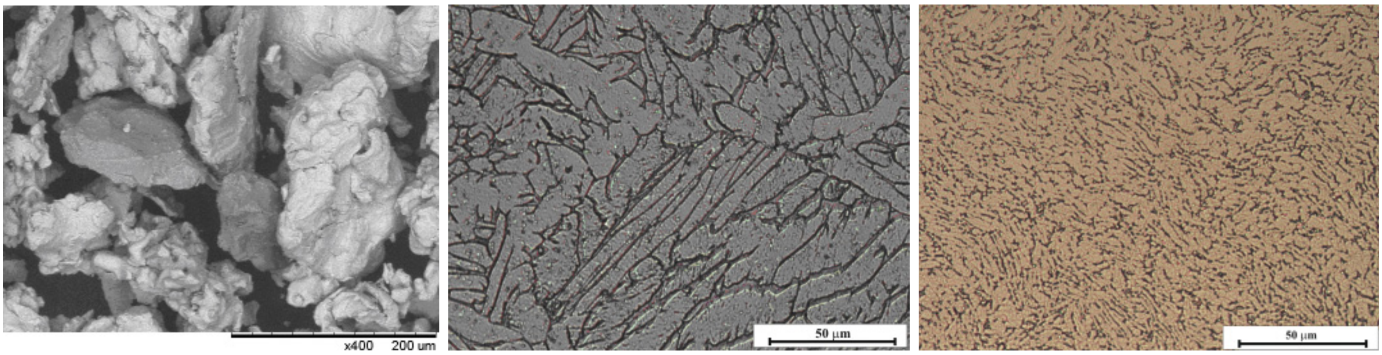
3. Results

The chemical composition specific for Ti-6Al-4V alloy is given in Table 1. Fig. 1a shows the morphology of the mixture of titanium, aluminium and vanadium elemental powders, while the microstructure of as-delivered cast and P/M compact are presented in Figs. 1b,c.

TABLE 1

Chemical composition of Ti-6Al-4V alloy (ISO 5832/3)

O	V	Al	Fe	H	C	N	Ti
<0.20	3.5-4.5	5.5-6.75	<0.30	<0.0015	<0.8	<0.05	Bal.



a) b) c)

Fig. 1. Morphology of the mixture of titanium, aluminium and vanadium elemental powders (a) and microstructure of initial materials: b – P/M compact, c – cast

Results of plastometric tests. Basing on upsetting tests, the flow curves of Ti-6Al-4V alloy were constructed, as a function of type of stock and the assumed temperature and strain rate. The variations of stress vs. strain obtained as a result of upsetting of compacts and casts are presented in Fig. 2. The stress required for the realization of a given strain is slightly lower in case of materials produced by means of powder metallurgy. In the first stage of test, the increase of true stress is observed for all specimens tested. With increasing strain, the change of character of curves is apparent and the stresses decrease, which proceeds faster in case of compacts. The only exception is the cast specimen upset at the temperature of 850°C and strain rate of 20 s^{-1}, where the decrease of stress was not observed. The obtained relationships may be used as a database for numerical simulations as well as for the selection of favorable parameters when designing the process of plastic working of the alloy.

Observations of the microstructure and hardness measurements of specimens after upsetting. The observations were made on longitudinal sections, in the central region. Fig. 3 presents the selected microstructures of Ti-6Al-4V alloy, in a form of compacts and cast material, upset under the assumed test conditions.

The microstructure of upset specimens of Ti-6Al-4V alloy depends on type of stock and test conditions. In case of the material obtained by means of powder metallurgy, deformed at temperatures of 850 and 900°C, the microstructure shows lamellar constitution with heavily elongated lamellae of a phase distributed in the matrix of b phase. The increase of upsetting temperature to 950°C results in obtaining a phase lamellae of larger thickness and the microstructure tends to show bi-modal character (Fig. 3c). No significant effect of strain rate on the microstructure was observed, only in case of high strain rates the regions of slight grain directionality could be seen (Fig. 3b). The observations of cast specimen, deformed at the temperature of 850°C, showed lamellar constitution. The upsetting of the cast at higher temperatures (900 and 950°C) resulted in obtaining bi-modal microstructure composed of uniformly distributed equiaxed grains of primary a phase and lamellar a+b colonies, being the effect of transformed b phase (Fig. 3e,f).

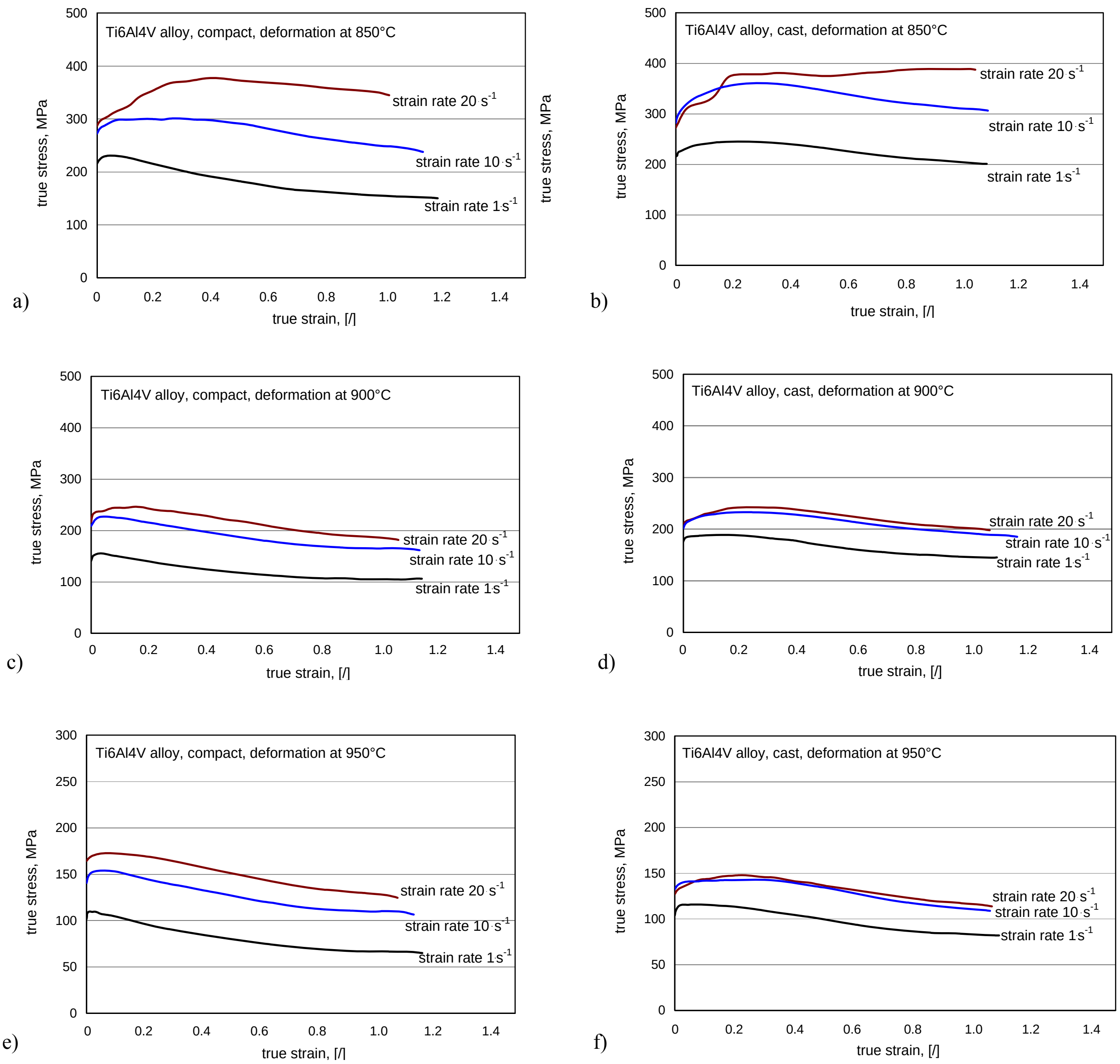


Fig. 2. Influence of upsetting conditions on the character of stress-strain curves, for specimens of Ti-6Al-4V alloy obtained by means of powder metallurgy (a-c) and casting (d-f).

Hardness measurement. Vickers hardness (HV_2) of specimens in the state after upsetting was measured on longitudinal sections, in the central region. Fig. 4 presents the distributions showing the averaged results of HV_2 hardness measurements as well as standard deviation of hardness. The highest HV_2 values were obtained for compacts after deformation at temperature 850°C. In case of a compact and a cast of Ti-6Al-4V alloy, the change of upsetting conditions does not lead to significant hardness variations. The highest difference in hardness observed between specimens of the same type of stock amounted to less than 20 HV_2, the standard deviation in any case did not exceed the value of 10 HV_2. Higher hardness of the material obtained by means of powder metallurgy was observed, when compared with the casts after upsetting under the same conditions. It was found that under the assumed conditions, the factors determining the hardness are the state of initial material and the schedule of heating, holding at specified temperature and cooling before upsetting. The effect of deformation conditions on hardness is insignificant, which confirms the results of microstructure observations. The hardness of materials before deformation was measured, it amounted to 316,6 ±2,8 HV_2 for cast material and 338,4 ±3,4 HV_2 for P/M compact. These values are lower than those observed in specimens after upsetting, regardless of the temperature and strain rate.

Industrial forging tests. Taking advantage of the results of plastometric tests and microstructure observations, forging process parameters were selected and then verified in industrial conditions. The shape of a forging was selected (Fig. 5a) and the stock dimensions were designed. The forging process was realized in industrial conditions, using the existing processing line. Fig. 5b presents the image of the example forging obtained. The filling of the impression was satisfactory and no cracks or other visible surface defects were detected.

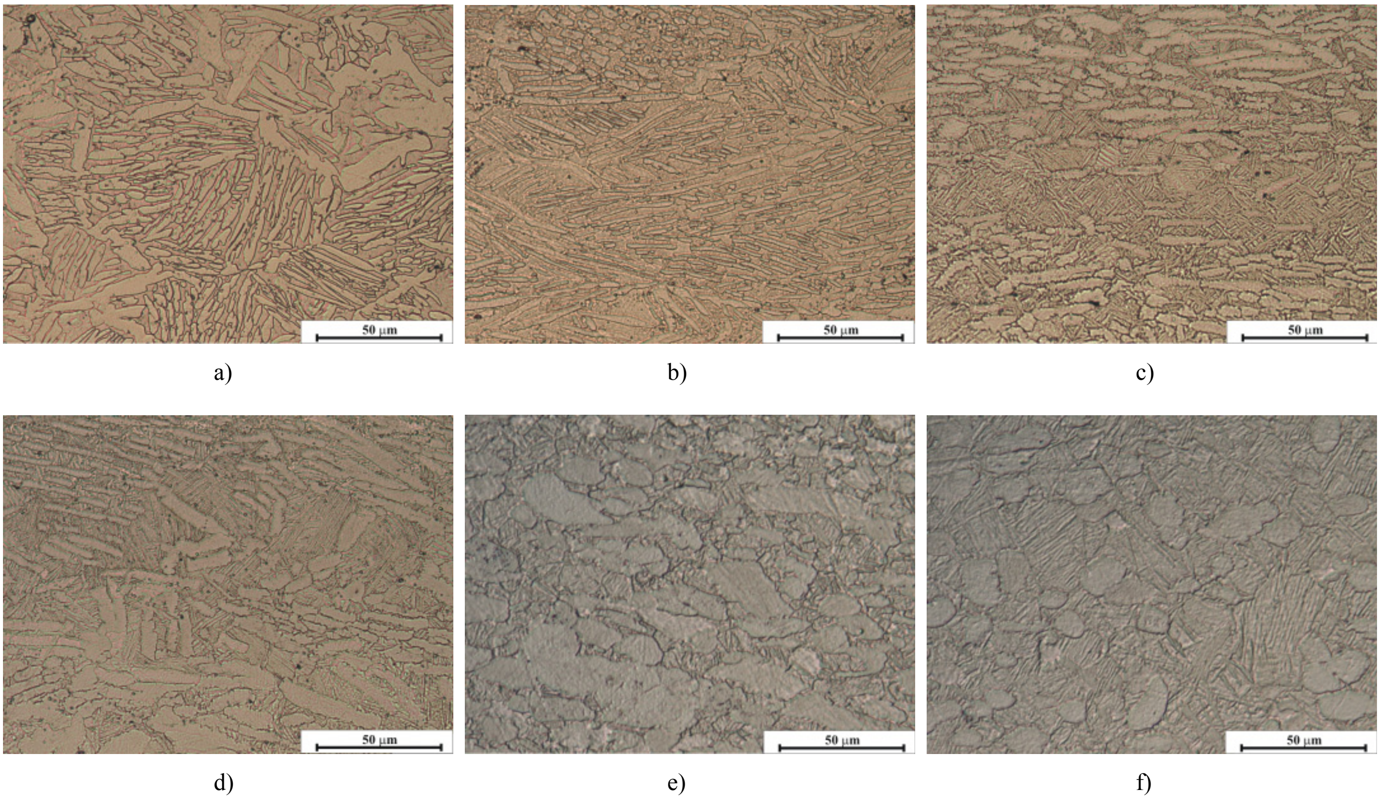
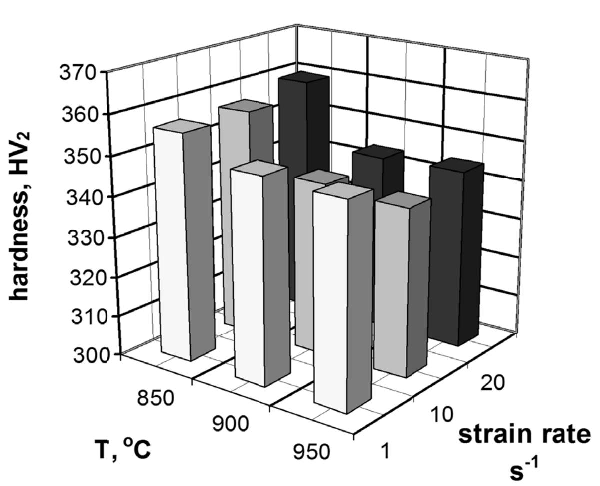
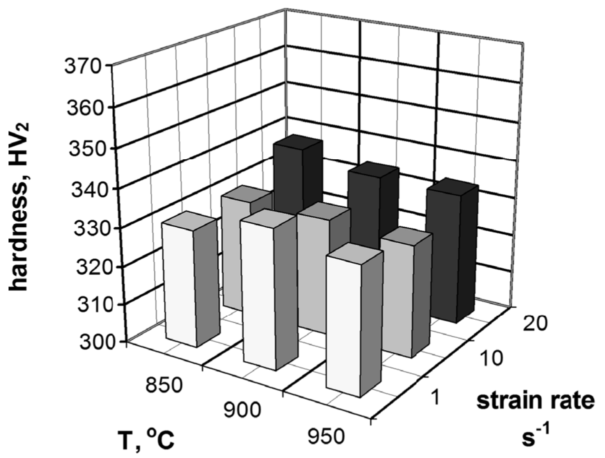


Fig. 3. Microstructure of Ti-6Al-4V alloy after deformation in WUMSI simulator: a,b,c – compacts, d,e,f – cast. Test conditions: a,d – temperature 850°C, strain rate 1, b,e – temperature 900°C, strain rate 20, c,e – temperature 950°C, strain rate 10. Longitudinal sections, specimen axis region, etched



	850 °C	900 °C	950 °C
$1{\cdot}s^{-1}$	357±4.6	351±4.8	350±5.2
$10{\cdot}s^{-1}$	357±3.2	343±4.5	342±3.7
$20{\cdot}s^{-1}$	360±5.8	344±5.1	345±4.4

a)



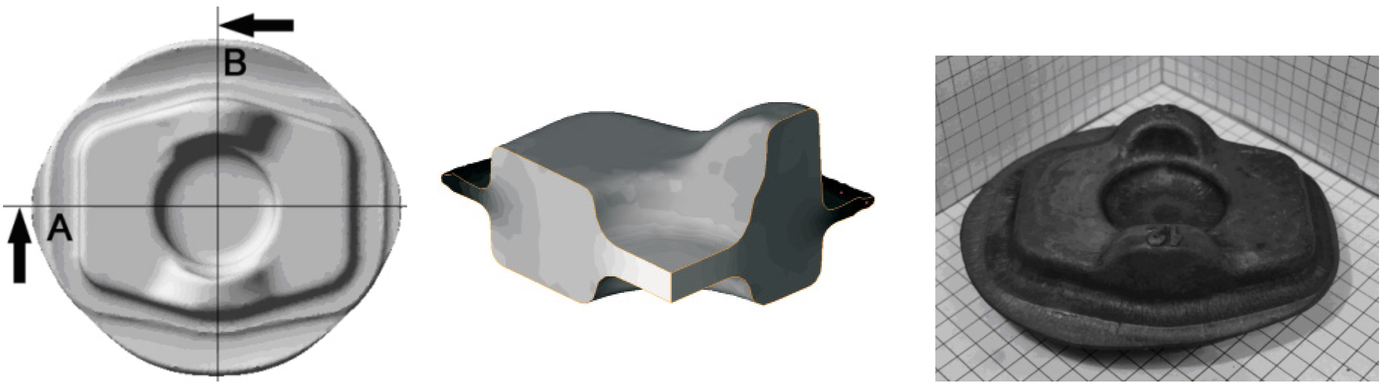
	850 °C	900 °C	950 °C
$1{\cdot}s^{-1}$	330±6.3	336±7.5	333±5.9
$10{\cdot}s^{-1}$	330±6.7	330±3.4	329±4.0
$20{\cdot}s^{-1}$	338±8.3	334±6.0	334±2.9

b)

Fig. 4. Influence of the type of initial material and deformation conditions on HV_2 hardness of Ti-6Al-4V alloy obtained by means of: a – powder metallurgy, b – casting

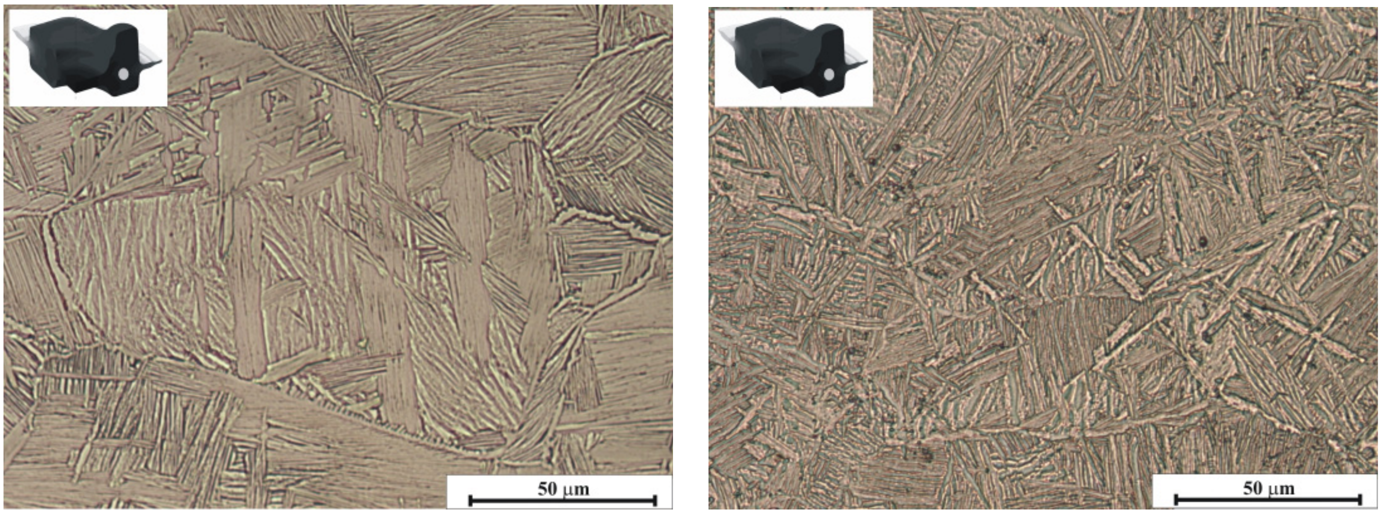
Observations of microstructure of forgings. The specimens for metallographic examination were taken from the longitudinal sections of forgings. Fig. 6 shows the region in a central part of a forging, in which metallographic observations were performed (a pale spot on the model), as well as the microstructures observed within that region.

Forging under the assumed conditions resulted in obtaining the microstructure showing lamellar constitution, which was found for both types of stock. The microstructure of a forging obtained from PM compact (Fig. 6b) is more refined within the region under observation, when compared with the product of the same shape obtained from cast (Fig. 6a). No cracks were detected



a) b)

Fig. 5. Shape of the forging selected for industrial trials: a – the model, b – the photograph of the example forging



a) b)

Fig. 6. Microstructure of a forging Ti-6Al-4V alloy obtained from the stock in a form of: a – cast, b – P/M compact. Etched sections

on metallographic specimens, thus confirming the conclusions based on the preliminary observation of a forging, concerning its quality. In case of a forging produced from the P/M stock, there were also no pores observed.

4. Summary

Basing on the upsetting tests it was found that the character of variations of stress as a function of strain, for materials obtained by means of powder metallurgy and casting, shows the differences. The microstructure of deformed specimens depends mainly on the type of stock and deformation temperature. In case of compacts, it is composed of the lamellae of a phase distributed in the matrix of b phase. The increase of upsetting temperature to 950°C results in obtaining a phase lamellae of larger thickness. In case of casts, the occurrence of two types of microstructure was observed, i.e. the lamellar type resulting from deformation at the temperature of 850°C, and bi-modal type observed at higher test temperatures. Since during die forging the strain rate varies and is also diversified within the volume, low sensitivity of Ti-6Al-4V alloy to strain rate may lead to obtaining uniform microstructure and properties, and this concerns both casts and compacts. Hardness measurements confirm this conclusion. It was shown that in case of proposed research schedule, the factors determining the hardness of the investigated materials of Ti-6Al-4V alloy are the state of initial material and the schedule of heating, holding at specified temperature and cooling before upsetting, while the effect of strain rate on hardness is insignificant. The die forging process parameters selected basing on the results of investigations were correct. The forging tests realized in industrial conditions resulted in proper filling of the die impression. No visible defects were observed on the surface of a forging, which was confirmed in metallographic examination. The results of investigations collected in this work show that the microstructure and properties of a stock obtained by means of casting and manufactured basing on elemental powders differ from each other. Therefore, the knowledge available in the literature, concerning the conditions of plastic working of cast Ti-6Al-4V alloy, cannot be directly applied when designing the processes of forming of compacts. The information collected in this work may be useful for the selection of suitable parameters of plastic working of P/M compacts, especially by means of forging.

Acknowledgements

Financial support of the Polish Ministry of Science and Higher Education is gratefully acknowledged (AGH-UST statutory research project no. 11.11.110.292).

REFERENCES

[1] C. Chunxiang, H. BaoMin, Z. Lichen, L. Shuangjin, Mater. Design **32**, 1684 (2011).

[2] O.M. Ivasyshyn, A.V.Aleksandrov, Mater. Sci. **44**(3), 311 (2008).

[3] M. Wojtaszek, T. Śleboda, A. Czulak, G. Weber, W. Hufenbach, Archives of Metallurgy and Materials **58**(4), 1261 (2013).

[4] R. Boyer, G. Welsch, E.W. Collings, Materials Properties Handbook, Titanium Alloys, eds. ASM Internat. Materials Park, OH, 1994.

[5] M. Long, H.J. Rack, Biomaterials **19**, 1621(1998).

[6] S. Yan-Wei, G. Zhi-Meng, H. Jun-Jie, Y. Dong-Hua, Procedia Eng. **36**, 299 (2012).

[7] P. Heinl, L. Müller, C. Körner, R.F. Singer, F.A. Müller, Acta Biomater. **4**, 1536 (2008).

[8] T. Fujita, A. Ogawa, Ch. Ouchi, H. Tajima, Mater. Sci. Eng. A**213**, 148 (1996).

[9] G. Lutjering, J.C. Williams, A. Gysler, Microstructure and Properties of Materials **2**, 1-74 (2000).

[10] V.A.R. Henriques, P.P. Campos, C.A.A. Cairo, J.C. Bressiani, Mater. Research **8**(4), 443 (2005).

[11] S. Bednarek, A. Łukaszek-Sołek, J. Sińczak, Arch. Civ. Mech. Eng. **8**, 13 (2008).

[12] D.P. Delo, H.R. Piehler, Acta Mater. 47(9), 2841 (1999).

[13] C. Haasea, R. Lapovoka, H. Pang Nga, Y. Estrina, Mater. Sci. Eng. A**550**, 263 (2012).

[14] O.M. Ivasishin, K.A. Bondareva, V.I. Bondarchuk, O.N. Gerasimchuk, D.G. Savvakin, B.A. Gryaznovb, Strength of Mater. **36**(3), 225 (2004).

[15] V.M. Anokhin, O.M. Ivasishin, A.N. Petrunko, Mater. Sci. Eng. A**243**, 269 (1998).

[16] A. Łukaszek-Sołek, J. Krawczyk, Key Eng. Mater. **641**, 190 (2015).

[17] M. Wojtaszek, T. Śleboda, Thermomechanical processing of P/M Ti-6Al-4V alloy. In METAL 2013, 22^{nd} Inter. Conf. on Metallurgy and Materials. Ostrava, TANGER, 364-369 (2013).