DEVELOPMENT OF THE PARAMETERS OF FORGING PM Ti6Al4V ALLOY FOR USE IN INDUSTRIAL CONDITIONS

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Abstract

This research work was focused on the application of powder metallurgy technology to the production of high-quality products from Ti6Al4V alloy (Ti64). The common way to produce structural parts from Ti64 alloy is hot forging. At present, the stock for forging is commonly manufactured from cast material. An attractive alternative for producing such billets can be powder metallurgy technology (P/M). The processing of compacts makes it possible to reduce the cost of production and leads to obtaining very good quality of the microstructure and properties. It is also very important, that this process can be realised using commercial processing lines for forming the cast stock.

The proposed procedures of development and verification of the parameters of deformation of Ti6Al4V alloy compacts in open-die forging process were discussed. As the material under investigation, compacts obtained from elemental powders were applied. The compacts were nearly free from porosity, which was confirmed by computed tomography non-destructive tests. The numerical modeling of hot forming of the selected forging was performed based on the finite element method (FEM). Various combinations of forging conditions were simulated, however the range of parameters was in accordance with possibilities of the industrial line. The results of modeling were verified in the trials conducted in industrial conditions. The quality of the product was estimated by the examinations of the microstructure as well as hardness measurements. It was found, that forging of billet, manufactured with application of the proposed powder metallurgy technology, leads to obtaining a defect-free Ti6Al4V alloy part.

Keywords: Powder metallurgy, titanium alloys, hot forging, thermo-mechanical parameters, microstructure

1. INTRODUCTION

Titanium alloys are applied in aircraft, automotive and medical industries as well as in many other industrial sectors [1, 2]. Their suitability for producing highly responsible components is due to the properties of titanium, of which low density, fatigue strength, crack resistance and corrosion resistance are particularly important [3]. They also exhibit high strength under dynamic load conditions [4]. The disadvantages of titanium and its alloys include low thermal conductivity and machining difficulties [5]. The high cost of manufacturing is also a significant factor limiting the range of their application [6]. Ti6Al4V is the most commonly used titanium alloy, which, in addition to the advantages of titanium, has high heat resistance, good weldability and ductility, what in properly chosen conditions enables its processing in metal forming processes such as hot forging [7]. In this case, the cast alloy is most commonly used as a feedstock, but more and more attempts are made towards using charge material prepared by powder metallurgy route. This approach offers the opportunity to reduce production costs by using cheap starting materials and waste-free, energy-saving processes [8]. If priority is given to economic considerations, the proper choice of the starting material is very important. Prealloyed powders (PA) or blended elemental powders (BE) can be used in this role. Obtaining a titanium alloy product based on a mixture of powders is technologically simpler and much cheaper, so this method of producing the starting material is now seen as having good prospect of implementation. Current research activities in this field concern, among others, the development of such technologies of manufacturing the products from powder mixtures, that lead to the homogenization of the chemical composition. One of the methods of achieving this is hot pressing of powder blends and further processing of blended powder compacts. Hot pressing with properly selected parameters allows obtaining a product of relative density ranging even more than 99% [9]. At present, Ti6Al4V alloy industrial processing is most commonly realized by extrusion, die forging and rolling. These processes can also be used to process powder compacts [9,10]. In this way the range of possible product geometries extends to long, flat or complex geometry products. The advantage of forming compacts under precisely controlled conditions is also the ability to influence the microstructure, and hence the properties of the product [11].

2. EXPERIMENTAL WORK

2.1. Purpose and scope of the investigations

The aim of the study was to develop and verify the favorable thermo-mechanical open die forging parameters for obtaining forged part of chosen geometry using Ti6Al4V alloy compact as a charge material. The scope of research covered the characteristics of the selected properties of the compacts, determining the profitable parameters of forming the forgings of selected geometry by numerical analysis, and conducting forging trials in industrial conditions under analytically determined conditions and verification of designed process conditions by the obtained forgings hardness measurements as well as the observations of their microstructures.

2.2. Investigated material characteristics

Ti6Al4V alloy obtained by hot pressing of the mixture of Ti, Al and V powders showing average particle size below 150 µm (-100 mesh), was used as the starting material for laboratory tests and industrial forging trials. The chemical composition of the alloy is shown in **Table 1**. Hot pressing process was carried out at 1200 °C under 25 MPa for 4 hours under argon protective atmosphere.

Table 1 The chemical composition of Ti6Al4V alloy obtained from the mixture of Ti, Al and V powders (wt.%)

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.

2.3. The investigations of the powder compacts

The compacts were subjected to density, metallographic and computer tomography (CT) non-destructive tests.

Relative density tests of the compacts were performed basing on Archimedes method. The average density of the compacts measured using this method was 99.4 ± 0.14%. The obtained result showed high densification of powder mixture under chosen conditions of hot pressing.

Computer tomography (CT) tests were performed at the Institute of Lightweight Engineering and Polymer Technology of TU Dresden in Germany. Diagram showing the location of an exemplary scan plane and sample scanned on this plane is shown in **Figure 1**. The observations of the internal structure of the compacts at 50 µm resolution showed no pores. On the basis of the evaluation of CT results, the occurrence of continuous defects such as cracks or delamination has also been excluded. The results of the non-destructive tests indicate that the compacts, hot formed under the proposed conditions, can be used as a charge material for the production of structural parts.

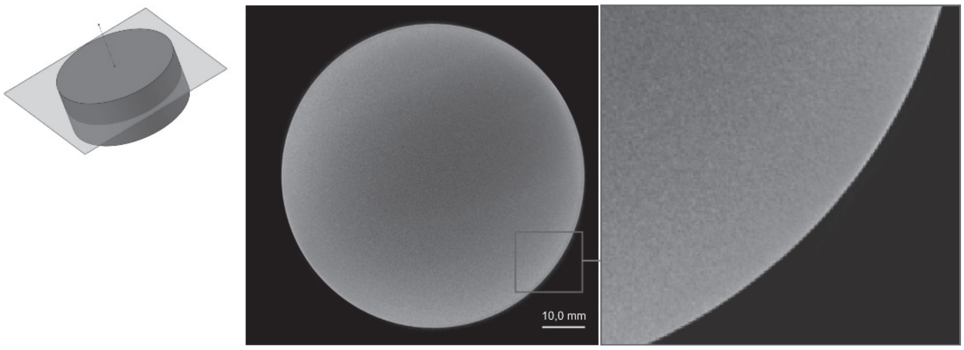


Figure 1 Schematic representation of the location of the observed cross-section of the sample machined from the compact and selected computed tomography (CT) image of this cross-section with magnified fragment shown on the right side

The observations of the microstructure of the compacts were carried out using light microscopy (Leica DM4000 M microscope). The cross-sections were etched in two steps using 6% HF in H_2O and then 2% HNO_3 + 2% HF in H_2O. The microstructure of the compact is shown in **Figure 2**. It consists of thick α phase plates located in the β phase matrix and at the grain boundaries. Relatively homogeneous nature of the microstructure signifies, that the homogenisation of the chemical composition took place in the processed compacts during hot pressing under the assumed conditions. The areas of α-phase plates were also observed on the investigated cross-sections. This may suggest a locally elevated concentration of vanadium stabilizing β-phase at the areas of primary vanadium powder particles location. Single spherical pores and very small pores were observed on the cross-sections examined under high magnification (**Figure 2B**) which confirmed small relative porosity revealed by the Archimedes method.

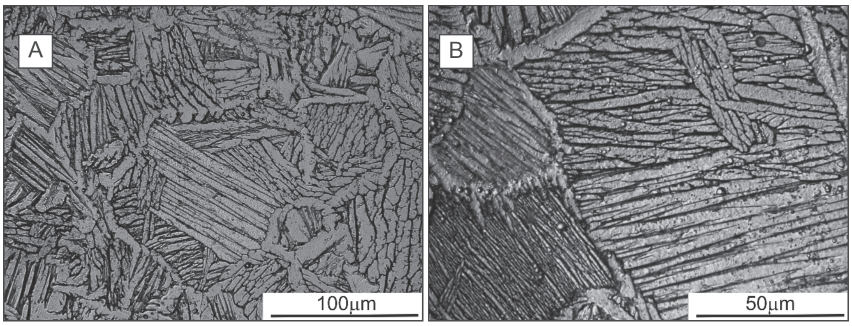


Figure 2 Microstructure of Ti6Al4V alloy compact. Cross-sections at the center of the compact

2.4. Modeling of hot open die forging of the compacts

Basing on the results obtained at this stage of the investigations, numerical modeling of open die forging of powder compacts using Finite Element Method (FEM) was performed. The FEM analysis was designed and conducted using QuantorForm 3D V8 software. The geometry of the forged part is shown schematically in **Figure 3A**. The boundary conditions necessary for modeling were obtained from the compression tests performed on the Gleeble 3800 thermomechanical simulator. The flow curves [9], developed on the basis of plastometric tests, were introduced into the QuantorForm 3D software, what allowed proper modeling of the material flow. Basing on the preliminary results of the numerical simulation, a cylindrical charge with diameter of 40 mm and height of 37 mm was selected. Advantages and limitations of industrial conditions were taken into account in the performed simulations. The temperature of the lower and upper die in the die cavity zone was assumed to be 250 °C. The simulations included heating the charge material up to the temperature of

1000 °C, cooling it down in the die cavity to chosen temperature and forging in one stage. The maximal speed of the upper die was 450 mm/s.

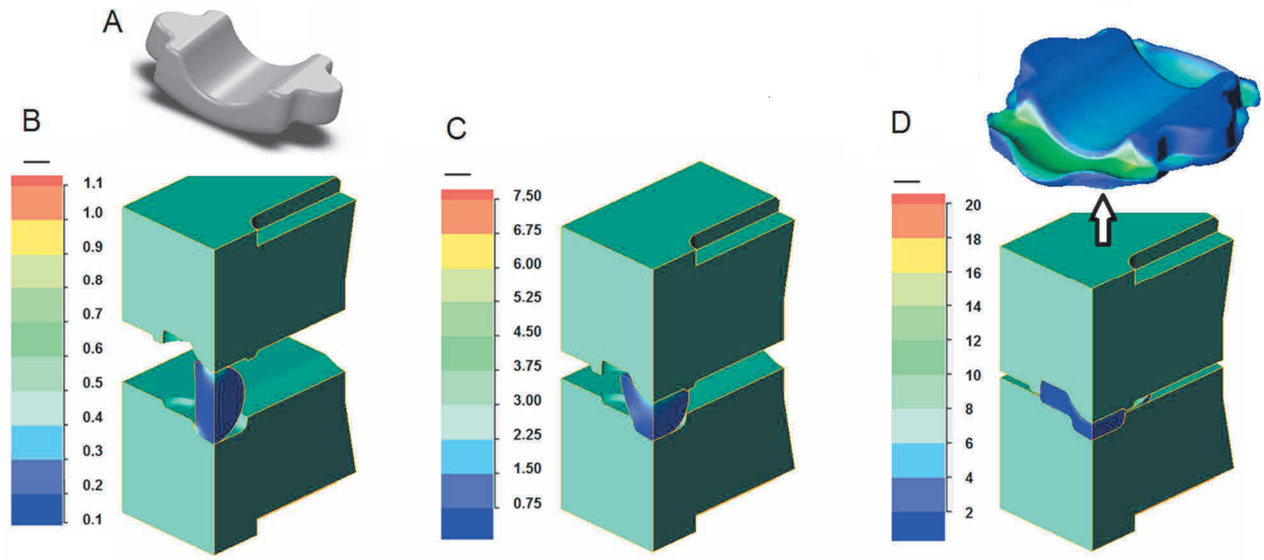


Figure 3 Geometry of the forging (A) and geometry of a billet in selected stages of open-die forging obtained from FEM numerical modeling, with corresponding effective strain distribution; B - initial stage, C - intermediate stage, D - final stage

Figures 3 B, C, D show exemplary results of FEM analysis obtained from modeling the forging at the temperature of 900 °C, which for the test material was determined to be advantageous under high speed of forging press tools. The comparison shows the changes in the geometry of the charge in the selected open die forging stages and the corresponding equivalent strain distribution in the volume of the forged part. The results of numerical modeling showed, that open die forging under chosen conditions leads to the correct filling of die cavity. It has also been found, that the most favorable flow of the material and, consequently, the filling of die cavity can be obtained by placing the charge material on its lateral surface, crosswise to the direction of the larger dimension of die cavity **(Figure 3A**), due to its better stabilization in the initial forging stage. No laps were observed in the volume of the forged part. FEM analysis showed high values of the equivalent strain at the final stage of forging in forging flash and adjacent forging areas as well as in the area of contact between forged material and lower die (**(Figure 3C**). In the remaining part of the forged material the distribution of equivalent strain was uniform, what is advantageous.

It was found that the results of the modeling under assumed conditions indicate the possibility of correct filling of die cavity and obtaining the product without any forging defects, what had to be verified.

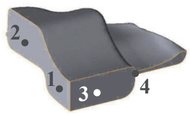
2.5. Verification of thermo-mechanical conditions for hot forging of powder compacts based on industrial trials

The verification of thermo-mechanical hot forging conditions, determined by laboratory tests and numerical simulations, was carried out in industrial conditions in the BELOS PLP S.A. (Poland) forging plant. The product with the same geometry as used in numerical modeling was forged. A cylindrical charge of the dimensions assumed in numerical modeling was prepared for forging. Forging dies were heated up to the temperature of 250 °C, the samples (charge material) and dies were lubricated. The charge was heated up to the temperature of 1000 °C, then placed in a die cavity in the screw press, cooled down to the temperature of 900 °C and forged in open dies in one stage. Tool speed was 450 mm/s, forgings were cooled in air. In the result of the hot forging trials, under the conditions determined by FEM modeling, a proper filling of forging die cavity occurred. Forgings with the proper geometry and without visible external defects were obtained. Preliminary control of their geometry indicated, that the thermo-mechanical parameters of forging of powder compacts and the assumed process conditions were properly designed, what was verified by the observations of the microstructure of the obtained forgings.

2.6. The investigations of forgings

Hardness measurements were conducted by Vickers method. The average hardness values HV_2 obtained from the 6 measurements, depending on the testing areas in selected zones lying in the symmetry plane of the forging, are summarized in **Table 2**. Similar hardness HV_2 results were obtained, what should be considered as advantageous. One exception to this was the zone placed near the forging flash, where the hardness was slightly higher. For comparison, the mean hardness of the compact was also determined, which was 338 ± 14 HV_2. In the result of the hot forging process under assumed thermomechanical conditions, the hardness of the material increased in all tested areas.

Table 2 The average values of HV_2 hardness on selected cross-sections of Ti6Al4V forging

	area	**1**	**2**	**3**	**4**
	HV_2	374 ± 10	366 ± 7	366 ± 12	388 ± 14

The microstructure of the forgings was observed on their cross-sections, whereby the cutting of the specimens was made in such way, that the cross-sections coincided with the planes of sample symmetry. Preparation of the cross-sections and their observations were carried out in the same way as for the compacts. **Figure 4** shows the location of the cross-sections where investigations and microstructure observations were made.

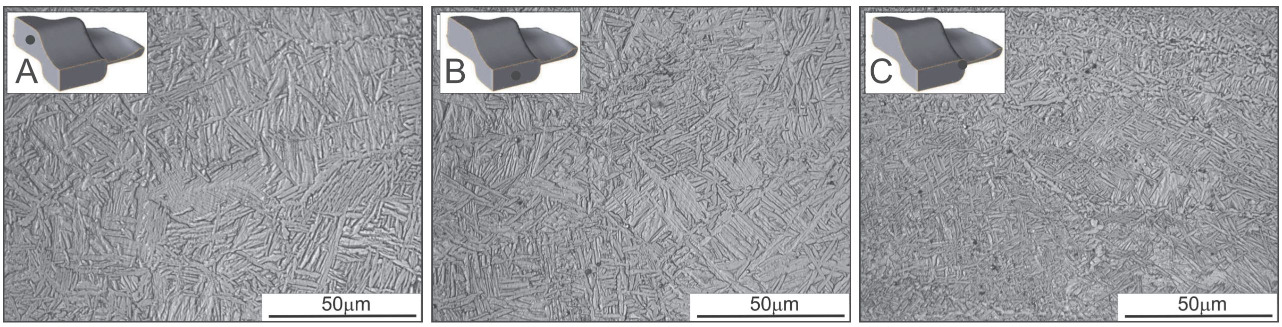


Figure 4 The microstructures of the forged part obtained by forging of compact. Cross-sections after etching

The forging microstructure (**Figure 4**) consisted of α-phase plates in β phase matrix. The size of the observed plates varied, but those differences were small. The strongest refinement of the microstructure was observed in the forging-flash transition zone (**Figure 4C**), what corresponds to the high values of equivalent strain shown in this area by the FEM modeling. Regardless of the test area, the plates visible on the cross-sections were significantly smaller (thinner and shorter) than that observed in the case of the compacts (see **Figure 1** and **Figure 4**). This applies, in particular, to α phase plates that have precipitated at the grain boundaries. No pores were observed on the observed cross-sections. No other forging defects were also observed, including areas adjacent to the outer surface of the forging.

3. SUMMARY

It has been found that the applied method of forming compacts leads to obtaining high density semi-product, that can be used to further processing, what was confirmed by microstructural observations and CT tests. FEM modeling of the open die forging of structural part of chosen geometry enabled determining the geometry of charge for forging and a method of its location in forging die cavity and allowed to indicate potentially favorable conditions for this process. The correctness of modeling results has been verified on the basis of industrial tests. In the result of the forging trials performed on screw presses in industrial conditions, forgings of desired geometry have been obtained. Metallographic tests of forgings have confirmed the correctness of the assumed forging parameters. The observed microstructure consisted of plates whose size only slightly depended on the cross-section of the forging area. The plates observed in the microstructure of forgings were much thinner and finer than those observed in the microstructure of the compacts. No pores or other internal defects were observed. The HV_2 hardness of the forging was higher than that of the charge material and reached similar values in different forging areas, which is advantageous in terms of the forged part quality. The proposed technology of processing Ti6Al4V alloy powder compacts can lead to obtaining free from defects final product of desired geometry. It has been shown that the correct development of thermomechanical forging conditions and their control during the realization of the forming process gives the possibility of modifying the microstructure and, consequently, obtaining a product with the required properties.

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REFERENCES

[1] CHUNGXIANG, C., BAOMIN, H., LICHEN, Z., SHUANGJIN, L. Titanium alloy production technology, market prospects and industry development. *Materials and Design*, 2011, vol. 32, pp. 1684-1691.

[2] IVASYSHYN, O. M, ALEKSANDROV, A. V. Status of the titanium production, research, and applications in the CIS. *Material Science*, 2008, vol. 44, no. 3, pp. 311-327.

[3] BOYER R., WELSCH, G., COLLINGS, E. W. *Materials Properties Handbook: Titanium Alloys*. 4th ed. ASM International, Materials Park, OH, 2007, 1176 p.

[4] WOJTASZEK, M., ŚLEBODA, T., CZULAK, A., WEBER, G., HUFENBACH, W. A. Quasi-static and dynamic tensile properties of Ti-6Al-4V alloy. *Archives of Metallurgy and Materials*, 2013, vol. 58, no. 4, pp. 1261-1265.

[5] YAN-WEI, S., ZHI-MENG, G., JUN-JIE, H., DONG-HUA, Y. Effect of spheroidization of Ti-6Al-4V powder on characteristics and rheological behaviors of gelcasting slurry. *Procedia Engineering*, 2012, vol. 36, pp. 299-306.

[6] FUJITA, T., OGAWA, A., OUCHI Ch., TAJIMA, H. Microstructure and properties of titanium alloy produced in the newly developed blended elemental powder metallurgy process. *Materials Science and Engineering*, 1996, vol. A213, pp. 148-153.

[7] LUO, S., ZHU, D., HUA, L., QIAN, D., YAN, S. Numerical analysis of die wear characteristics in hot forging of titanium alloy turbine blade. *International Journal of Mechanical Sciences*. 2017, vol. 123, pp. 260-270.

[8] LIU, Y., CHENA, L. F., TANG, H. P., LIU, C. T., LIU, B., HUANG, B. Y. Design of powder metallurgy titanium alloys and composites. *Materials Science and Engineering A*, 2006, vol. 418, pp. 25-35.

[9] WOJTASZEK, M., ŚLEBODA, T. Thermomechanical processing of P/M Ti-6Al-4V alloy. In *METAL 2013:* 22nd *International Conference on Metallurgy and Materials*. Ostrava: TANGER, 2013, pp. 364-369.

[10] JIA, M., ZHANG, D., LIANG, J., GABBITAS, B. Porosity, microstructure and mechanical properties of Ti-6Al-4V alloy parts fabricated by powder compact forging. *Metallurgical and Materials Transactions A*, 2017, vol. 48, no. 4, pp. 2015-2029.

[11] QIU, J.W., LIU, Y., LIU, B. LIU, B.Y., WANG, B., RYBA, E., TANG, H. P. Optimizing the hot-forging process parameters for connecting rods made of PM titanium alloy. *Journal of Materials Science*, 2012, vol. 47, pp. 3837-3848.