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Effect of Cyclic Close Die Forging on Microstructure and Mechanical Properties of Ti – 5Al – 3Mo – 1.5V Alloy

Truong An Nguyen[1], Manh Hung Le[2], Manh Tien Nguyen[1,*], Quoc Viet Pham[3]

[1] Le Quy Don Technical University, Faculty of Mechanical Engineering Hanoi, Vietnam
[2] General Department of Military Industries and Manufacture, Institute of Technology Ha Noi, Viet Nam
[3] General Department of Military Industries and Manufacture, Military Industrial College Phu Tho, Vietnam
* Correspondence: manhtiennguyen84@gmail.com
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Abstract: The goal of this work is to study the effects of cyclic close die forging on microstructure and mechanical properties of Ti – 5Al – 3Mo – 1.5V alloy, which was produced in Viet Nam. The factors considered include deformation temperature (T_d) from 850⁰C, 900⁰C and 950⁰C and the number of cycles performed while forging in closed die (n) of 3, 6 and 9 times. The response is average grain diameter (d_{tb}) and tensile stress (σ_b). The results indicated that the smallest average grain size 1 μm could be obtained at T_d = 900⁰C, n = 9 times and the tensile stresses are enhanced. The experimental results we obtained also suggest that the microstructure of Ti – 5Al – 3Mo – 1.5V alloy is accordant for superplastic deformation. The superplastic forming of this alloy can show maximum elongation of 1000% or more.

Keywords: Superplastic deformation; Cyclic closed die forging; microstructure; average grain size, Ti – 5Al – 3Mo – 1.5V alloy.

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1. Introduction

Titanium alloy is a structural material with many outstanding properties: high strength, small density, good ductility, high melting point and outstanding corrosion resistance. Therefore, titanium alloy is increasingly used in many different technical industries, especially in the aviation, automotive, and defense industries [1]. However, at room temperature, the durability of titanium alloy is very large, making it difficult to cut, so it is usually deformed at high heat in the range from 600 ÷ 1050⁰C [2].

In order to improve the applicability of titanium alloys in practice, it is necessary to study methods to improve mechanical properties and improve technology, especially to improve the deformation ability of materials. One of the measures to improve deformation capacity is the need to prepare the workpiece with fine grain and deformation under reasonable conditions of strain temperature and rate. Meanwhile, the titanium alloy is deformed in the superplastic state [3, 4].

Superplasticity is the ability of plastic deformation to a large extent of a metal or alloy under certain conditions of the microstructure, temperature and strain rate under the impact of small stress and depends on the strain rate [5]. For uniaxial tension tests, the elongation to fracture above 200% is usually indicative of superplasticity, although some materials can be achieved extension up to 1000%. it shows that such values are greater by one or two orders of magnitude compared to those of conventional metallic materials. The superplastic state is characterized by three basic signs: a very large degree of plastic deformation, which can reach hundreds or even thousands of percent without destroying the material; the stress needed to deform the material in the superplastic state is very small compared to the plastic deformation in the normal state; the yield stress is very sensitive to changes in strain rate which means that metal tendency can harden by the strain rate [6, 7].

In order to appear structural superplastic, three conditions must be ensured: microstructure of material, deformation temperature and strain rate. Metals and alloys have a fine and stable microstructure (usually between 5÷15 μm) and the particle size is almost unchanged during deformation. The temperature range of deformation to superplastic deformation is quite wide, usually ranging from (0.5 ÷ 0.9) T_{nc} (T_{nc} - melting point of the material in degrees Kelvin). The deformation temperature must ensure no change during deformation and uniformity throughout the workpiece. The strain rate must be small enough for diffusion to occur and must be large enough at high temperatures to ensure that the particles do not grow during machining. Normally, the strain rate of superplastic deformation usually ranges from (10^{-4} ÷ 10^{-2}) s^{-1} [5, 6, 7].

The methods that can be used to give the material a fine grain structure is the severe plastic deformation (SPD). Severe plastic deformation (SPD) is the group of metalworking techniques involving very large strains typically involving a complex stress state or high shear, resulting in a high defect density and equiaxed ultrafine grain (UFG) size (d < 500 nm) or nanocrystalline (NC) structure (d < 100 nm) [8, 9].

In the methods of SPD, the cyclic closed die forging (CCDF) method is the method that can allow to obtain materials with very fine microorganisms, even nano - organization for industrial alloy grades. It can be carried out over a wide temperature range (20 ÷ 950)°C by using specialized mold structures and heaters; allows the deformation of workpieces with large sizes and volumes compared to some other methods such as [9, 10]: high pressure twisting, pressing through a broken channel ... Besides, requirements for equipment, tools, and molds for The deformation is quite simple, easy to fabricate, and at the same time highly capable of industrial applications.

The technology parameters of the CCDF method affecting the structure and mechanical properties of the titanium alloy include the deformation temperature and the number of deformation times. In the present work the influence of CCDF carried out in the temperature range between 800 and 900^{0}C and the number of deformation times on the structure and properties of Ti – 5Al – 3Mo – 1.5V titanium alloy was studied.

2. Experimental procedure

2.1. Materials

The material used in this study was an σ/β titanium Ti – 5Al – 3Mo – 1.5V alloy. The Ti - 5Al - 3Mo - 1.5V titanium alloy is produced in Vietnam. The test specimens are in the casting state. The rectangular specimens of width 17 mm and length 17 mm and height 25 mm was used for the experiment (Fig 1). The chemical composition of the analyzed Ti – 5Al – 3Mo – 1.5V alloy is shown in Table 1.

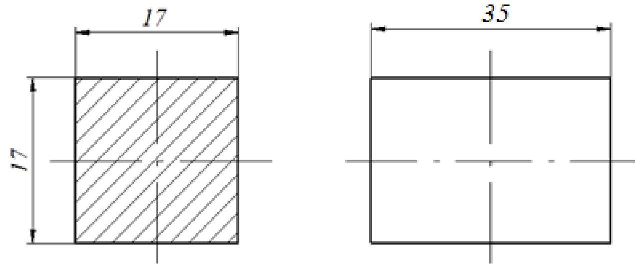


Figure 1. The specimen for experiment

Table 1. Chemical composition of the analyzed Ti – 5Al – 3Mo – 1.5V alloy (%Wt)

Element	Al	Mo	V	Zr	Si	Fe	O	N	Ti
Wt%	5.36	3.27	1.54	0.30	0.045	0.152	0.037	0.015	Balance

2.2. The experimental method

The CCDF process is performed in steps and cycles in a closed die. The deformation cycle consists of three steps I, II, III. The forging dies and the order of steps per cycle are shown in Fig 2. The initial workpice is marked with faces as A, B, C, which correspond to the coordinate axes of X, Y, and Z.

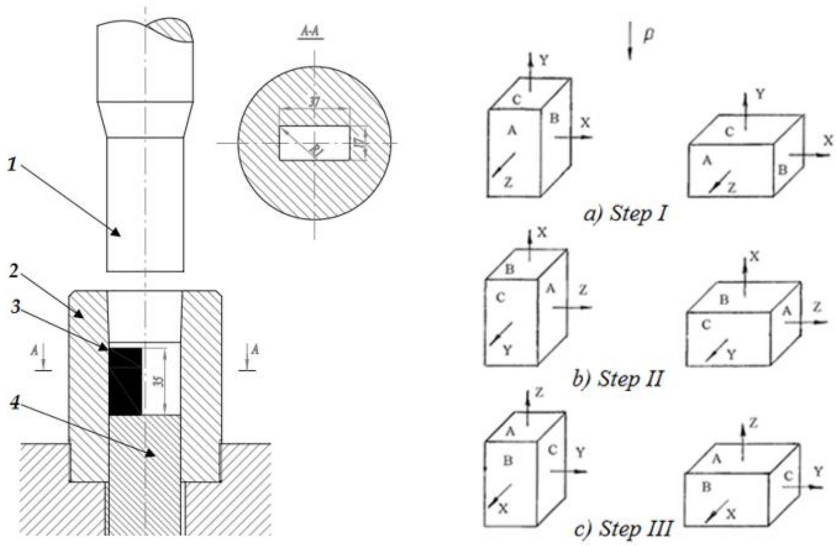


Figure 2. The forging dies and the steps of CCDF process
(1) Punch; (2) Die; (3) Workpice; (4) Ejector

In step I (Fig 2a), when the punch is pressed down, the height of the workpiece in the Y direction is reduced, the size of the workpiece is stretched in the X direction, the size of the workpiece in the Z direction does not change due to restriction by the die.

In step II (Fig 2b), the workpiece is removed from the mold after step I, placing the workpiece in the mold so that the direction of the pressure coincides with the X direction (rotates the workpiece by 90°). After deformation, the workpiece size along the X axis decreases with the pressing stroke, the workpiece size in the Z axis is increased, the workpiece size in the Y axis remains constant.

After the end of step II, remove the workpiece and rotate the workpiece to 900 and perform step III of the cycle pressing (Fig 2c). In this step, the workpiece is reduced in size in the Z-axis, the dimension increase in the Y-axis, the dimension on the X-axis remain constant.

By deforming over a number of cycles (1÷3 cycles), the workpiece is deformed relatively evenly along the axis, which will help improve the microstructure and mechanical properties of the material, especially the fine stable grain size will be obtained and increase the plastic deformation ability.

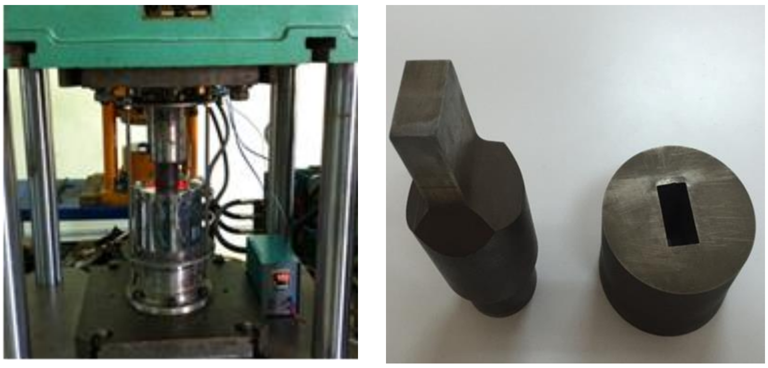
2.3. Experimental conditions and equipments

Nine experimental specimens were deformed by the cyclic closed die forging with the deformation temperature and number of deformation times shown in Table 2. The cyclic closed die forging process is performed by 100 tons hydraulic press (YH32 – 100T). The strain rate of the workpiece depends on the pressing speed of the experimental equipment, which was about 1 mm/s.

Table 2. The experimental parameters

No.	Deformation temperature (^{0}C)	Number of deformation times (times)
1	850	3
2	850	6
3	850	9
4	900	3
5	900	6
6	900	9
7	950	3
8	950	6
9	950	9

The containers with the specimens were heated to the deformation temperature (850, 900 and 950^{0}C) in a Nabertherm chamber furnace LH120/13, and the specimens were then located into the working chamber of a forging die (Fig 3). The delay before beginning the extrusion was 20÷30 s. The heating process for the die is done on a furnace capable of heating up to 800^{0}C, with the fluctuation with the set temperature of ± 3°C.



(a) (b)

Figure 3. Scheme of CCDF set-up and tools (a) The experiment die; (b) Punch and die

The microstructure of the deformed samples was examined using a Nova - NanoSEM - 450 scanning electron microscope (SEM) and optical microscopy. Tensile test is performed on compression puller TT-HW2-1000. The tensile properties of the material deformed at deformation temperature were determined by a tensile test at room temperature. The tensile samples for the tensile test are presented in Fig 4.

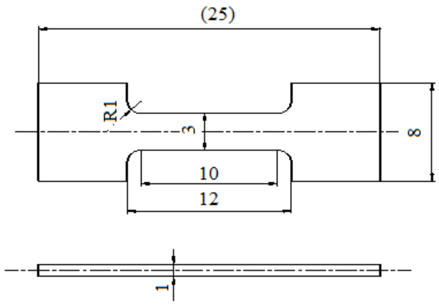


Figure 4. The specimen for the tensile test

The microstructure, texture and mechanical properties were determined on the central portion of the deformed samples where steady deformation occurred. Average grain size is determined according to ASTM E 112 (Standard Test Methods for Determining Average Grain Size) [11] or ISO 643: 2019 [12] (Micrographic determination of the appareent grain size).

3. Results and Discussion

The microscopic images in Fig 5 shows an average grain size about 300 μm. The mechanical properties of the initial test specimens are shown in the Table 3.

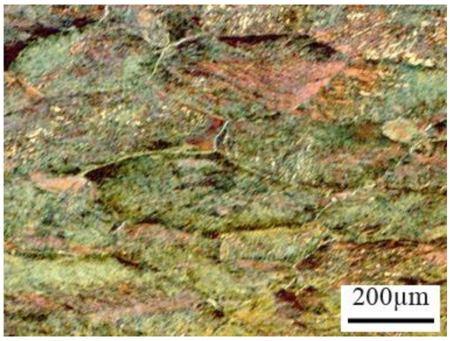
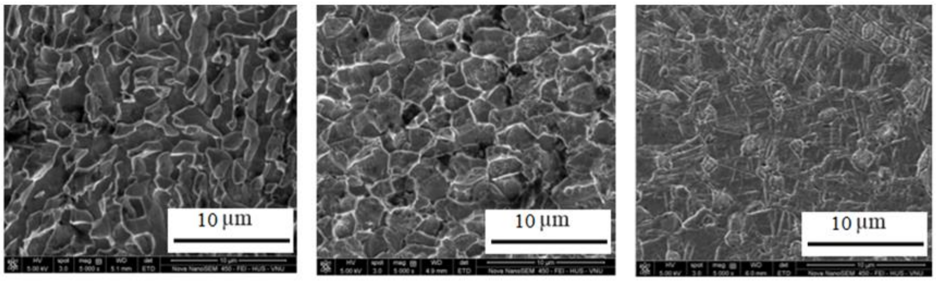


Figure 5. The microscopic of Ti - 5Al - 3Mo - 1.5V alloy of initial test specimens (x100)

Table 3. Mechanical properties of Ti–5Al – 3Mo – 1.5V alloy

Material	Ultimate tensile stress (MPa)	Hardness (HB)	Tensile elongation (%)	Reduction of area (%)
Ti - 5Al - 3Mo - 1.5V (casting state)	980	255 ÷ 341	≥7	≥28

Fig 6 shows the microstructure of some experimental specimens after CCDF with different strain temperature and number of deformation times, a small grain growth was noticed after the severe plastic deformation tests. Using the "Snyder-Graff" method [13], we can determine the average grain diameter on the microscopic images of the experimental specimens after CCDF process (Table 4).



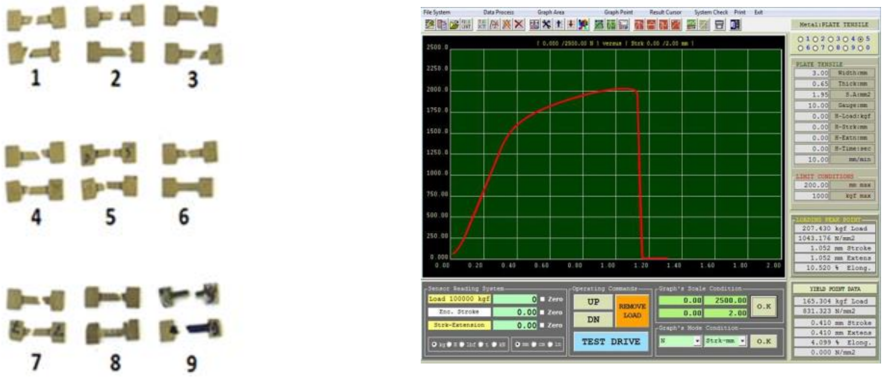
(a) **(b)** **(c)**

Figure 6. The microstructure of some experimental specimens after CCDF (x5000): (a) The No.3; (b) The No.5; (c) The No.9

Table 4. The average grain size of experimental specimens

No.	Number of grains/mm^2	Grain size index	Average grain diameter (µm)
1	382500	3	2.0
2	425000	6	1.4
3	435000	9	1.4
4	392500	3	2.0
5	455000	6	1.4
6	837500	9	1.0
7	75000	3	3.9
8	105000	6	2.8
9	125000	9	2.8

Tensile test specimens are also numbered (1 to 9) corresponding to the test conditions in Table 2. The tensile stress of the experimental specimens with different strain temperature and number of deformation times are given in Fig 7 and Table 5. The tensile test resulted in a noticeable enhancement of the mechanical characteristics compared to the initial alloy.



(a) **(b)**

Figure 7. The tensile results: (a) The specimens after tensile tests; (b) The tensile test chart after 9 deformation times at 950^{0}C

Table 5. Mechanical properties of Ti-5Al-3Mo-1.5V alloy after CCDF

No.	1	2	3	4	5	6	7	8	9
Ultimate tensile stress (MPa)	1362	1043	1266	1085	1117	1295	1055	1196	1142

From the experimental results, it was found that after the CCDF process, Ti - 5Al - 3Mo - 1.5V titanium alloy was significantly improved in microstructure. The average grain size is decreased significantly (Fig 8). However, it was found that at the pressing temperature of 950^{0}C the microscopic structure of the specimens was different because the specimens were deformed at temperatures above the A_{c3} region (phase transition temperature), so the microstructure obtained was phase α' (mactenxite), it is the over-saturated hexagonal α phase of Molipdenum and Vanadium [2]. At deformation temperature over 900^{0}C, the average grain size increases with increasing temperature, the smallest average grain size is obtained in the temperature range (870 - 900)^{0}C.

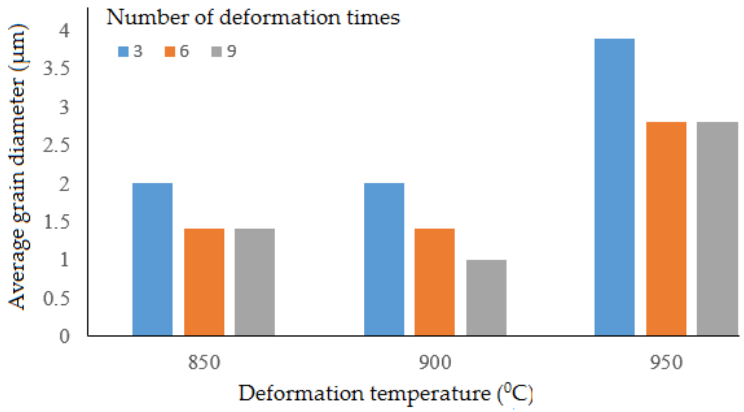


Figure 8. The average grain size of experimental specimens

The specimens after deformation by CCDF also significantly improve the mechanical properties. After 1 cycles (3 deformation times) to 3 cycles (9 deformation times) of CCDF, the ultimate tensile stress increases from (11÷43) % compared to the initial specimens (Table 5).

4. Conclusions

The main conclusions from the research results of the current work can be drawn as follows:

The CCDF of Ti - 5Al - 3Mo - 1.5V titan alloy at deformation temperature of 850 ÷ 950^{0}C and the number of deformation times from 3 to 9 times results in a considerable refinement of the microstructure. After one cycle of CCDF process (3 steps), the average grain size obtained approximately 3 ÷ 4 μm and after three cycles, the average grain size obtained about 1÷2 μm.

As the result of CCDF at 900^{0}C and 9 times of deformation, the alloy exhibits a very small average grain size whilst maintaining good mechanical properties. The average grain diameter and ultimate tensile stress of the alloy was 1 μm and 1295 MPa, respectively.

The Ti - 5Al - 3Mo - 1.5V alloy microstructure obtained after CCDF processes, which meets the superplastic forming conditions, in order to improve the plastic deformation ability of this alloy. The superplastic forming problems can be considered in the future work.

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