# STUDY OF GLOBULARIZATION IN TI-6AL-4V ALLOY DURING NON-ISOTHERMAL MULTIPLE FORGING AND ANNEALING

**[1]DIGVIJAY J. SHEED, [2]BHAGAWATI P. KASHYAP, [3]RAJKUMAR P. SINGH**

[1,3]bharat Forge Limited, Pune, 411036, India
[2]Department of Metallurgical Engineering and Materials Science, Indian Institute of Technology Bombay, Mumbai, 400076, India
E-mail: [1]Digvijay.sheed@bharatforge.com, [2]bpk@iitb.ac.in, [3]rajkumarsingh@bharatforge.com

**Abstract-** In present work the mechanisms of globularization i.e. breaking of initial α colony structure during multiple forging and post deformation annealing process at different temperatures (700°C to 950°C) has been analyzed. A workpiece (Ø94 mm x 120 mm) of Ti-6Al-4V alloy with starting initial α-colony structure was heated at 850°C and subjected to successive upsetting and drawing operations without intermediate heating, followed by water quenching. The deformed Ti-6Al-4V alloy consists of heterogeneous microstructure with kinked, sheared and unreformed α lamellae. Microstructure evolution mechanism during successive upsetting or drawing operations is proposed here. Globularization of thin inter-lamellar β phase was observed after post deformation annealing at 800°C. The process of static globularization was found to be accelerated by increase in annealing temperature above 900°C via mechanisms like boundary splitting, edge spheroidization and cylinderization.

**Index Terms-** Annealing, Globularization, Non-isothermal multiple forging, Ti-6Al-4V alloy

## I. INTRODUCTION

Titanium and titanium alloys especially Ti-6Al-4V alloy has wide applications in aerospace, marine, chemical, automobile engineering and biomedical science due to its high specific strength and corrosion resistance properties. In two phase (α/β) Ti-6Al-4V alloy, it is possible to tailor the microstructures by changing the heat treatment and thermo-mechanical processing (TMP) route [1]. The lamellar microstructure which is result of air/furnace cooling from β phase field in Ti-6Al-4V alloy is very difficult to breakdown into equiaxed or duplex microstructure. The lamellar structure has good crack growth resistance but poor ductility. On other hand, equiaxed structure contributes to good ductility but poor fatigue properties. Duplex microstructure gives good combination of ductility and fatigue properties [1-5]. During TMP and subsequent heat treatment process, the conversion of lamellar structure into equiaxed structure, called as globularization process, which is controlled by various parameters like deformation temperature, effective strain, annealing temperature etc. [2-5]. Various models have been proposed to explore the globularization mechanism during deformation as well as post deformation static annealing [5-9]. Wises [7] explained that during hot deformation and subsequent annealing, formation of low or high angle α-α grain boundaries takes place within α lamellae, followed by penetration of β phase along α-α grain boundary, and thus replacing the original α lamellae by globularized α grains. Therefore, α-α grain boundary formation within α lamellae or substructure formation is very important process to transfer starting lamellar structure into equiaxed α structure. Second important mechanism of the globularization is fault migration or termination migration which supports the coarsening behavior of α lamellae at elevated temperature. The driving force comes from the existence of chemical gradient due to the difference in the curvature at the termination and flat interphase. There exist other mechanisms like edge spheroidization and cylinderization which can contributes in the globularization process. The objective of the present work is to understand the microstructure evolution and globularization mechanism during multiple forging which consists of repetitive upsetting and drawing operations as shown in Fig. 1 [10, 11] and subsequent post deformation annealing process at different temperatures.

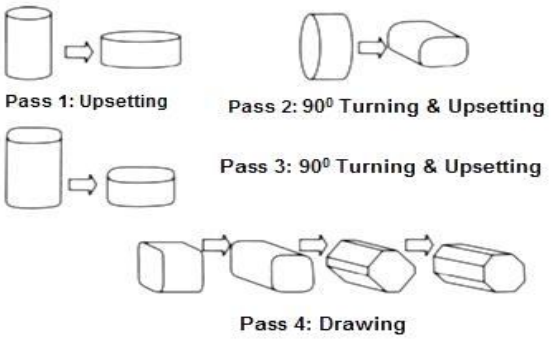



**Fig. - 1. Schematic representation of multiple forging [11]**

## II. MATERIAL AND EXPERIMENTAL PROCEDURE

A workpiece of size Ø94 mm x 120 mm was cut from as-received Ti-6Al-4V alloy billet. The chemical composition (wt. %) of as-received Ti-6Al-4V alloy was 6.48 Al, 4.28 V, 0.039 Fe, 0.015 C with 0.02 O and balance Ti. The β-transus temperature of

as-received material was ~ 995°C. The as-received Ti-6Al-4V alloy, consisting of α-colony structure within prior β grain with grain boundary α of average thickness ~ 4.2 μm as shown in Fig. 2, was used as starting microstructure for experiment. The starting microstructure was examined in the optical microscope (OM) and Scanning Electron Microscope (SEM). This revealed α phase volume fraction of 89 ± 3.3 % and average thickness of initial α lamellae ~ 2.5 μm. In order to prevent oxidation at elevated temperature workpiece was coated with Deltaglaze. This was then heated to 850°C with the help of gas fired furnace and soaked for 100 minute inside the furnace. The heated workpiece was taken manually to flat die on pneumatic hammer of 2500 lb capacity, in time span of 20 seconds. The upper and lower die was kept approximately at same temperature ranges from 200°C – 220°C.obtaining any security clearances.

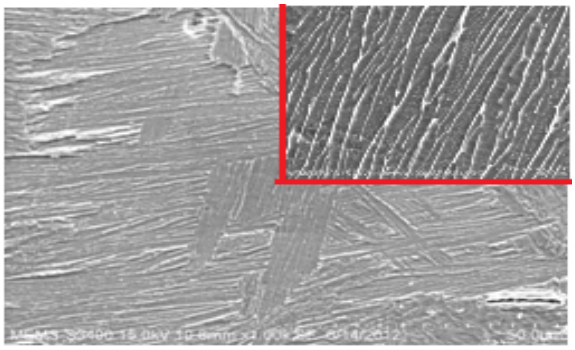


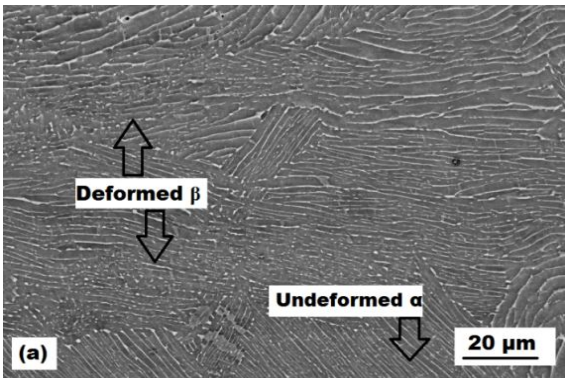
**Fig. 2 - SEM micrograph showing α-colony structure of as-received Ti-6Al-4V alloy, the inset shows distinct lamellar structure**

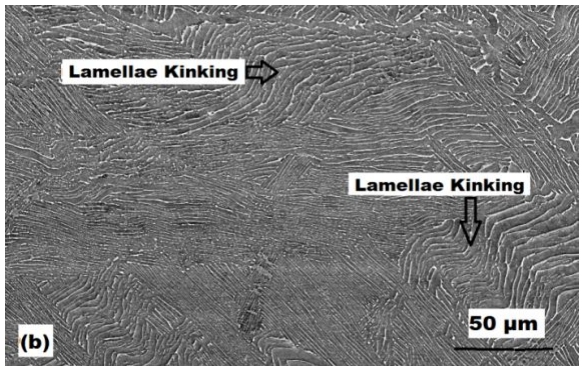
In multiple forging, the workpiece is generally subjected to successive upsetting and drawing operations in three directions. In present work, the workpiece was deformed in seven steps with repetitive upsetting and drawing operations. The final temperature of workpiece was measured to be ~ 705°C with the help of non-contact infrared pyrometer (Raytek make). After deformation, the workpiece was water quenched. During deformation in seven steps of upsetting and drawing operations, the workpiece was deformed to effective strain (ε) of ~ 1.5, without intermediate heating. Samples were cut from deformed workpiece at central portion along longitudinal direction (LD). The samples were subjected to post deformation annealing at four different temperatures viz. 700°C, 800°C, 900°C and 950°C for 2 hours. After heat treatment, the samples were water quenched. The deformed and annealed samples were mechanically polished on Struers automatic disc polisher equipment. Kroll's reagent (10% HF + 5%HNO3 + 85%H2O) was used as etchant to examine the microstructure in SEM. Microstructures and nature of grain boundaries were analyzed in samples annealed at 900°C and 950°C temperatures by electron backscattered diffraction (EBSD) analysis. An EBSD scans were carried out with scan area of 250 μm x 100 μm and step size of 0.15 μm using Carl-Ziess SEM equipped with OIM of Oxford laboratories.

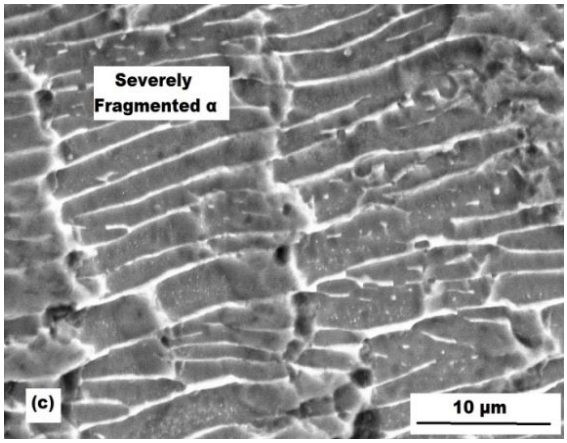
## III. RESULTS AND DISCUSSION

### A. Microstructure evolution after deformation

The initial starting α-colony structure was found to be very difficult to breakdown because of the microstructural stability associated with the plate like structure of α lamellae. In order to break α-colony structure into equiaxed structure significant effective strain ~ 2.5 to 3 was needed to be imposed during hot deformation [3, 6]. In this work, during successive upsetting and drawing operations, the workpiece was deformed to effective strain (ε) of ~ 1.5 and followed by water quenching. The changes in microstructure after deformation were observed along longitudinal direction (LD), parallel to the upsetting direction, in SEM as shown in Fig. 3 (a-d).



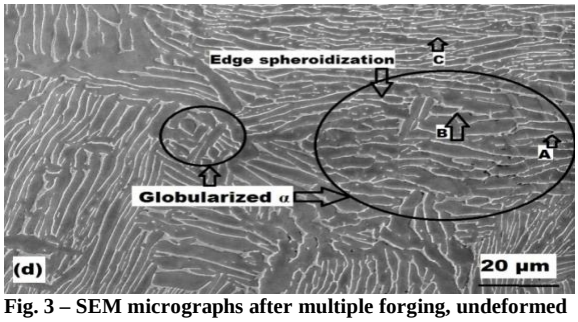



**Fig. 3 – SEM micrographs after multiple forging, undeformed α-colony structure with deformed β phase a) lamellae kinking b) fragmented α-lamellae c) globularized lamellar structure d)**

During plastic deformation the imposed strain is possibly accommodated by the rotation of α-colonies in the metal flow direction i.e. in the direction perpendicular to the upsetting direction, as shown in Fig 3a. The β phase observed is notably deformed and discontinues in α-colonies oriented in metal flow direction. It has been well studied that the α-colonies with certain orientations are very hard to deform [2-6]. Presence of undeformed α-colony is quite general as shown in Fig. 3a. The α-lamellae thickness which remains unchanged is measured to be ~ 3 µm. During deformation large plastic work is converted into heat. The distribution of the heat is non-uniform across the workpiece of Ti-6Al-4V alloy due to its low thermal conductivity. So, in Ti-6Al-4V alloy, heat is not carried away but it results into local flow softening or flow localization in that region i.e. active shear band. The flow softening causes uneven strain distribution to result into non-uniform microstructure [2-4]. Along with undeformed α lamellae, deformation instabilities like lamellae bending or buckling also called as kinking was observed as shown in Fig. 3b. The possible mechanisms of α-lamellae fragmentation during deformation is well documented in literature [3-7]. In multiple forging, change in the deformation direction helps to activate number of slip systems in hexagonal closed packed (hcp) α-titanium [11-12]. The severe fragmentation of α lamellae was observed as shown in Fig. 3c- as result of multiple forging. The β phase became discontinuous and having non uniform thickness. The fragmentation of α lamellae possibly occurred via shearing as well as boundary splitting mechanism. The possible mechanism of α lamellae fragmentation during multiple forging is explained by schematic model shown in Fig. 4

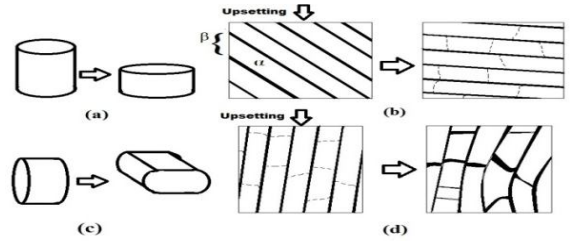
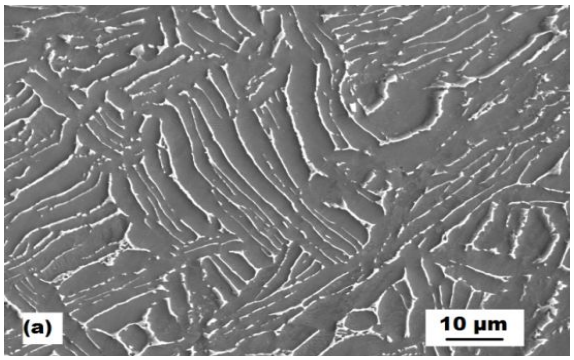


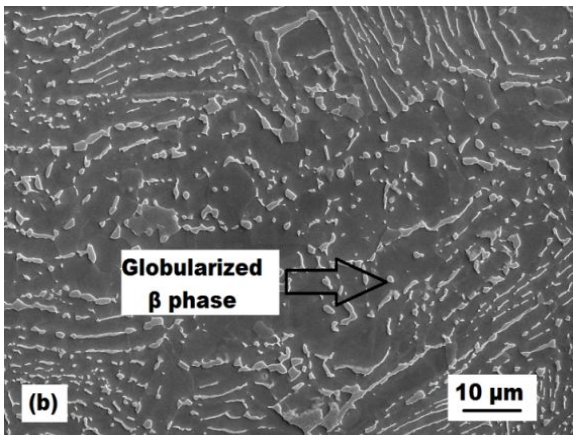

**Fig. 4 – Schematic of α lamellae fragmentation during multiple forging, (a) First upsetting (b) Sub structure formation and rotation of α lamellae in the direction of metal flow during first upsetting (c) 90 ° rotation of workpiece and second upsetting (d) fragmentation of α lamellae via shearing and bending**

In multiple forging, during first upsetting the deformation is possibly accommodated by the rotation of α lamellae in the direction of metal flow as well as the formation of low and high angle grain boundaries in α-lamellae, depending upon the strain induced, as shown in Fig. 4a-b. During successive upsetting operation, the rotation of α lamellae may be possibly resisted by fragmentation or the formation of low and high angle grain boundaries in α lamellae in first and second upsetting operations. During the second upsetting, fragmentation of α lamellae occurs along the low and high angle grain boundaries formed in α lamellae via gross local shearing or boundary splitting mechanisms as shown in the Fig. 4c-d. The severely fragmented α lamellae via shearing and bending is shown in Fig. 3c. In Fig. 3d, fully globularized or formation of low aspect ratio α lamellae also observed. A, B and C shows the formation of low aspect ratio α lamellae via shearing and edge spheroidization. It might be possible due to the lower deformation temperature; boundary splitting mechanism, suppressed by shearing or bending mechanism.

B. Microstructure evolution after post-deformation annealing

Microstructure evolution after post-deformation annealing at 700°C, 800°C, 900°C and 950°C are shown in Fig 5a-d respectively. The conversion of the deformed α lamellae occurs via different mechanisms like boundary splitting, termination migration, edge spheroidization and cylinderization mechanisms during deformation as well as during annealing process.



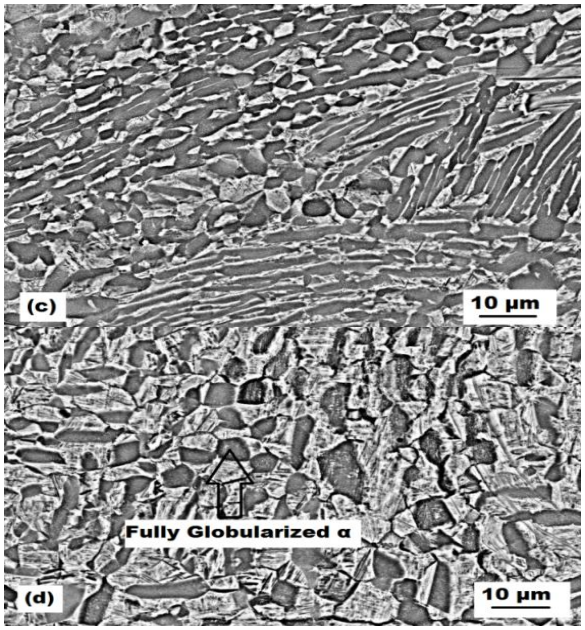



**Fig. 5 – SEM micrographs after post deformation annealing for 2h at 700°C a) 800°C b) 900°C c) and 950°C d)**

The microstructure remains stable with no change in α phase morphology/aspect ratio after postdeformation annealing at 700°C as shown in Fig 5a. No signs of boundary splitting or thermal grooving were observed. After post deformation annealing at 800°C, β phase splitted and globularized into small globules. The splitting and globularization of β phase and slight coarsening of α phase could be the result of termination and migration mechanism. The mechanism of boundary splitting was to be found accelerated with increase in annealing temperature with diffusion of β phase along α-α boundary leading to noticeable change in the aspect ratio of α lamellae observed at 900°C, as shown in the Fig 5c. At 950°C the interfacial energy along α-α boundaries reduced to prevent the further diffusion of β phase along α-α boundaries [5, 7-10]. The further separation and globularization of fragmented α lamellae having aspect ratio less than ~ 4 took via cylinderization mechanism. Completely globularized α phase particles suspended in the transformed β phase appeared after annealing at 950°C as shown in the Fig. 5d. The variation of aspect ratio of the lamellae with respect to post deformation annealing temperature is shown in Fig. 6.

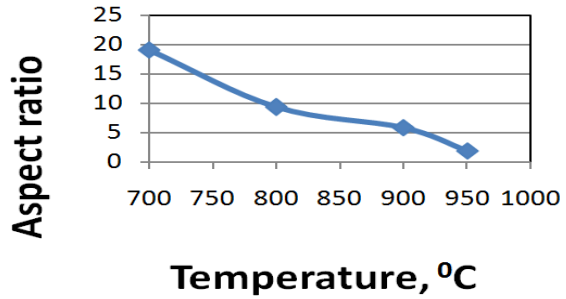



**Fig. 6- Variation of α lamellae aspect ratio vs annealing temperature**

The mechanism of globularization process during annealing at 900°C and 950°C was further studied with inverse pole figure (IPF) maps as shown in the Fig. 6a-d.

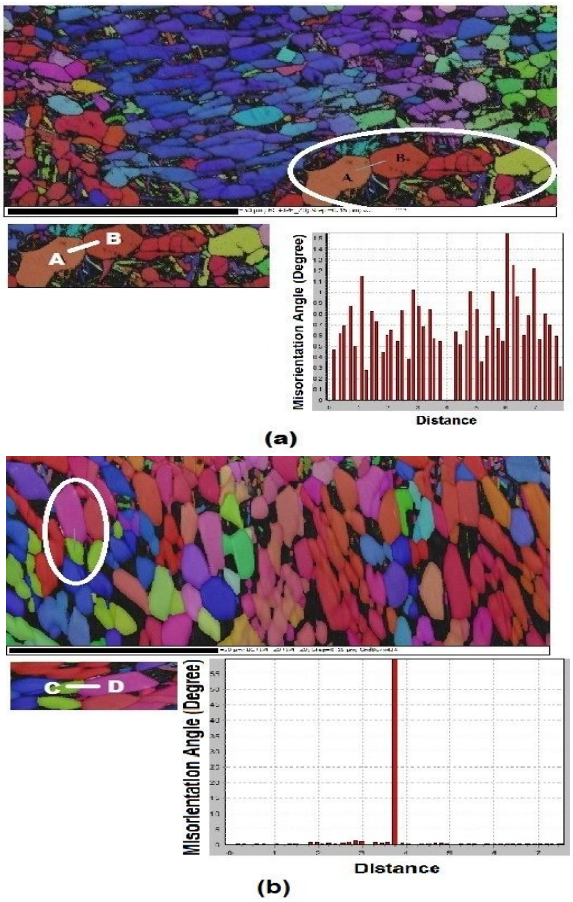



**Fig. a) IPF map of Ti-6Al-4V alloy sample after post deformation annealing a) at 900°C with misorientation graph across line AB b) at 950°C with misorientation graph across the α-α grain boundary (line CD), globularized within same parent α lamellae**

Fig. 6a shows the fragmented cluster of α lamellae or substructure of α lamellae of same orientation appearing within transformed β matrix after post deformation annealing at 900°C. The transformed β matrix consists of very fine secondary α phase. The black noise in IPF map is non-indexed transformed β phase. In fragmented cluster of α lamellae, which possibly formed within same α colony, shows no significant thermal grooving or separation of α-α grain boundary via diffusion of β phase as noted. In contrast, significant thermal grooving was observed in kinked or buckled α lamellae as marked by circle in Fig 6a. The misorientation profile across line AB marked over α-α grains, derived from same α lamellae, was plotted as shown in Fig. 6b. α grains derived from same α lamellae by boundary splitting mechanism have same orientation as observed previously by Weiss [7]. A completely globularized α grains with transformed β phase at the triple point junction was observed after post deformation annealing at 950°C, Fig. 6c. It is clear that the mechanism of boundary splitting

followed by cylinderization was accelerated at 950°C. The misorientation profile across line CD, marked on two α grains derived from same α lamellae, was plotted as shown in Figure 5d. It is possible that α grains derived from same α lamellae may have different orientation due to sub structure rotation or recrystallization in the absence of thermal grooving.

## CONCLUSION

The mechanisms of globularization during non-isothermal multiple forging and subsequent post-deformation annealing at different temperatures were investigated.

1. The starting α-colony microstructure was found difficult to break and result into heterogeneous microstructure consisting of undeformed, kinked and fragmented α lamellae structure.
2. In multiple forging, during successive upsetting and drawing operations, the fragmentation took place mostly by severe shearing of α lamellae. The globularization mechanism involves rotation of α-colony in metal flow direction and followed by severe shearing during successive upsetting operation along high angle grain boundaries.
3. During post deformation annealing, aspect ratio of α lamellae decreases noticeably with increase in annealing temperature. The process of globularization during annealing consists of separation of fragmented α lamellae via boundary splitting and ends with the cylinderization of low aspect ratio α lamellae.

## ACKNOWLEDGMENT

The authors gratefully acknowledge the extended support provided to present work by KCTI (Kalyani Centre for Technology and Innovation). The authors also acknowledge the support provided by Bharat Forge Ltd, Pune and DSIR, Govt. of India. The authors would also like to express special thanks and gratitude to review committee and top management of Bharat Forge Ltd for granting the permission to publish/present the research work.

## REFERENCES

[1] C. Leyens and M. peters "Titanium and Titanium alloy – Fundamentals and application", WILEY-VCH ,(2003)
[2] T. Seshacharyulu, S. C. Medeiros, W. G. Frazier, Y.V.R.K. Prasad, " Microstructural mechanisms during hot working of commercial grade Ti–6Al–4V with lamellar starting structure", Materials Science and Engineering A325, 112–125, (2002)
[3] S. Zherebtsov, M. Murzinova, G. Salishchev, S. L. Semiatin, " Spheroidization of the lamellar microstructure in Ti-6Al-4V alloy during warm deformation and annealing", Actamaterialia, 59, 4138-4150, (2011)
[4] S. L. Semiatin, V. Seetharaman, I. Weiss, " Flow behaviour and globularization kinetics during hot working of Ti–6Al–4V with a colony alpha microstructure", Materials Science and Engineering A263, 257–271, (1999)
[5] N. Stefansson and S. L. Semiatin, "Mechanics of globularization of Ti-6Al-4V alloy during static heat treatment", Metallurgical and Materials Transactions 34A, 691-998, (2003)
[6] R. Ding, Z. X. Guo, A. Wilson, "Microstructural evolution of a Ti–6Al–4V alloy during thermomechanical processing", Materials Science and Engineering, A327, 233–245, (2002)
[7] I. Weiss, F.H.Froes, D.Eylon, G.E. Welsch, "Modification of alpha morphology in Ti-6Al-4V by thermomechanical processing", Metallurgical Transactions A, 17A 1986-1935, (1985)
[8] J. C. MalzahnKampe, T. H. Courtney and Y. Leng "Shape instabilities of the plate-like structure-I experimental observations in heavily cold worked in situ composites", ActaMaterialia 37, 7 1735-1745 (1989)
[9] T. H. Courtney and J. C. MalzahnKampe "Shape instabilities of the plate-like structure-II Analysis", ActaMaterialia 37, 7 1747-1758, (1989)
[10] G. Sharma, R. V. Ramanujan, G. P. Tiwari, "Instability mechanisms in lamellar microstructures", Actamaterialia,, 48 ,875-889, (2000)
[11] R. Imayev, A. Nazarov, R. Mulyukov, "Principles of Fabrication of Bulk Ultrafine-grained and nanostructured materials by multiple isothermal forging", Materials Science Forum Vols. 638-642 1702-1707, (2010)
[12] S. V. Zherebtsov, G. A. Salishchev, R. M. Galeyev, O. R. Valiakhmetov S. Yu. Mironov, S. L. Semiatin, "Production of submicrocrystalline structure in large-scaleTi–6Al–4V billet by warm severe deformation processing", ScriptaMaterialia, 51 1147-1151, (2004)

★★★