Structure and Properties of Titanium Modified Silicon-carbide at EBM

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Abstract. Aim of the work is development of technology of production of ingots from sparsely-alloyed titanium alloys using electron beam melting method. To get high mechanical characteristics in titanium alloy, the modifiers of high-dispersion carbide compounds were used as foundry alloys. They in process of electron beam melting provide strengthened with nanoparticles structure of a material suitable for further deformation processing. In order to develop nanosized alloying modifiers for high-strength titanium alloys there were synthesized nanosized powder in form of carbon solution in silicon-carbide. A technology was developed for production of ingots from sparsely-alloyed titanium alloys using electron beam melting method. The works on production of 200 mm diam. titanium ingots with addition of 0.5% and 1.5% of the alloying modifiers based synthesized nanosized silicon-carbide were carried out with the help of determined modes. Hot deformation processing of ingots was performed, 15 mm thick deformed sheets were produced and then subjected to further heat treatment. Structure and properties of obtained material were investigated.

1. Introduction
Titanium alloys are the structural material, which has a lot of unique properties, among which, in this case, it is necessary to outline, first of all, high values of specific strength [1]. Today all over the world there is a stable tendency to increase the portion of high-strength materials, which provide high complex of mechanical and service properties and at that have good weldability [2-5]. The recent investigations show that some titanium alloys in application of special technologies for their production can provide 1600-1800 MPa strength, and in comparison with steel products of the similar strength the one produced from titanium have virtually two times lower weight. Sufficiently cheap high-dispersion compounds of carbides, nitrides and intermetallics can be used as a foundry alloy for development of high strength of titanium. They will provide in the process of melting the ingots with high-dispersion structure strengthened by nanoparticles suitable for further deformation processing.

2. Methodology
To get sparsely-alloyed titanium alloy it was decided to an use alloying element in form of silicon-carbide powder, which was added in necessary proportions to titanium sponge of TG-120 grade. The synthesis of SiC powder is based on reaction of self-propagating high-temperature synthesis (SHS) in specially designed graphite or ceramic crucibles of predetermined volume as well as at necessary temperature mode [6-7]. The appearance of obtained particles is given on Figure 1 and characteristics of produced powder in Table 1.
Figure 1. Appearance of microstructure of silicon carbide particles

Table 1. Characteristics of synthesized SiC powder

| Average size of grains, nm | Lattice parameters, nm | Content of impurity phases, % |
|---------------------------|------------------------|------------------------------|
| 70                        | 0.43486                | C       | SiN₄ | Si₂N₂O |
|                           |                        | 0.2     | 2    | 3      |

Among the current methods of special electrometallurgy the electron beam melting (EBM) is one of the efficient methods of vacuum metallurgy and it has found application in research practice and industry for production of alloys, including refractory and high-reactive, with ultra-low content of gases, volatile impurities and non-metallic inclusions [8]. EBM allows in a wide range regulating the ingot melting rate due to independent heat source that in turn permits regulation of time of metal staying in a liquid overheated condition. EBM is the most efficient technology that allows virtually complete elimination of inclusions of high and low density [9]. For experimental evaluation of the characteristics of proposed titanium alloys with addition as modifiers of 0.5% and 1.5% nanosized SiC powder there were carried out the trial melts of batches of 200 mm diam. ingots in electron beam unit UE-121.

The briquettes of rectangular form, which were pressed from TG120 grade titanium sponge of up to 30 mm fraction and addition of 0.5% and 1.5% of synthesized SiC powder (Figure 2) were used as charge materials for melting of a batch of titanium alloy ingot of 200 mm diam. In process of melting the consumable billet was continuously fed in a working zone over hearth, where its melting took place under effect of electron beam heating (Figure 3).
Figure 2. Pressed briquettes of titanium sponge with addition of nanosized SiC powder.

Figure 3. Prepared for melting fixture and process of melting of 200 mm diam. ingots of titanium alloy modifier with nanosized SiC particles.

Appearance of ingots after melting and next machining is presented on Figure 4.

Figure 4. Appearance of melted and machined 200 mm diam. ingots of titanium alloy with addition of 0.5% and 1.5% of nanosized SiC powder.

Ultrasonic flaw detection using UD4-76 flaw detector was used for determination in the ingots of internal defects in form of non-metallic inclusions, pores and discontinuities. Analysis of macrostructure of metal of produced 200 mm diam. ingots was carried out on transverse templates cut out of the produced ingots (Figures 5, 6).
Figure 5. Macrostructure of metal of 200 mm diam. ingot of titanium alloy with addition of 0.5% of SiC

Figure 6. Macrostructure of metal of 200 mm diam. ingot of titanium alloy with addition of 1.5% of SiC

The results of examinations show that a structure of ingot metal is dense, homogeneous, has no zones that have different etching on ingot cross-section. There is no significant difference observed in the structure of a central zone of ingot and peripheral zone. The defects in form of pores, cavities, cracks and non-metallic inclusions were not found. It is determined that increase of content of nanosized SiC in titanium results in significant refinement of macrostructure. Thus, according to GOST 26492-85 [10] the grain size in the metal of the examined ingots of titanium alloys with addition of 0.5 and 1.5% of nanosized SiC powder correspond to sizes 8 and 5, respectively.

The obtained samples of cast metal were used for performance of hardness investigations. Measurement of hardness was carried out on hardness gage TP-73-1 at 10 kg loading on diamond indenter. The measurement of material hardness on the templates in two mutually normal directions showed differences in hardness values not more than 5%. This indicates that the particles of alloying modifier have sufficiently uniform distribution over the whole ingot volume. The values of measurements are given in Table 2.

Table 2. Values of hardness of cast samples of ingots of titanium alloys with addition of SiC-based alloying modifiers

| Sample          | Hardness HV10.0, GPa | Hardness, HRC |
|-----------------|----------------------|---------------|
| Ti – 0.5%SiC    | 2.9                  | 29-30         |
| Ti – 1.5%SiC    | 3.3                  | 32-33         |

Analysis of data shows that rise of portion of alloying additive of the nanosized alloying modifier results in increase of cast metal hardness. Thus, further rise of portion of the nanosized alloying modifier can be not reasonable due to the fact that increment of hardness level of martial will lead to the difficulties or will make further deformation processing impossible.

Improvement of the mechanical properties of cast material to the necessary level is achieved by further application of technologies of deformation processing and heat treatment. Plastic deformation of the obtained ingots was carried out on a reversing duo rolling mill of Skoda 355/500 grade. Titanium alloy billets with addition of 0.5% and 1.5% SiC were subjected to hot plastic deformation firstly on hydraulic press P-457 with next rolling on a mill at 1050°C temperature without application of shielding atmosphere and shielding coatings. Deformed semi-finished products of 15 mm thickness are presented on Figure 7.
3. Results

The microstructure of titanium alloy doped with 0.5% of SiC at different magnifications is presented on Figure 8. The alloy consists of deformed primary $\alpha$-grains with considerably deformed boundaries, therefore determination of primary grains is complicated. The material mainly consists of lamellar $\alpha$ phase that makes the colonies of various size. The width of $\alpha$-phase lamellas makes 5-8 $\mu$m and length 50-150 $\mu$m. Photos made with large magnification allow observing the finest particles of another phase, size of which is less than 1 $\mu$m, uniformly distributed in the structure (Figure 8).

Figure 8. Microstructure of titanium alloy doped with 0.5% of nanosized alloying modifiers based on SiC.

Figure 9 shows the microstructure of titanium alloy doped with 1.5% of SiC. In the same way, as the previous alloy, this titanium alloy consists of deformed primary grains with split boundaries. The main phase constituent of the alloys is lamellar $\alpha$ phase, width of particles of which makes 4-6 $\mu$m and length 30-70 $\mu$m, i.e. lamella of $\alpha$ phase with addition of 1.5% of SiC is finer than in alloy with 0.5% of SiC. In addition to lamellar $\alpha$ phase in Ti+1.5%SiC alloy it is possible to find in a small amount unknown for us phase with clear boundaries in form of round, oval or elongated particles with 2-4 $\mu$m width and 2-12 $\mu$m length (Figure 9). To understand the nature of the described phase constituent the further investigations are necessary. In the structure of researched alloy Ti-1.5% SiC there is also presence of a disperse phase of 1 $\mu$m size and less. The similar phase constituent was observed in the research alloy Ti+0.5%SiC, however, there it is even smaller and uniformly distributed in the metal volume.
Obtained mechanical properties of the designed alloys correspond to structural states that are realized in the process of only hot rolling without additional thermal processing. As it can be seen from Table 3, increase of concentration of nanosized silicon carbide leads to decrease of ductility and rise of strength.

Cold rolling was carried out at maximum 10% level of deformation per one pass. The total level of deformation did not exceed 60%. Cold rolling of hot-rolled titanium alloy results in strength growth and decrease of ductility (Table 3). Such dependence is proved by known dependence of properties on level of stress that is caused by formation of the dislocations in the structure at cold deformation.

| Composition       | Yield limit $\sigma_y$, MPa | Short-term tensile strength limit $\sigma_t$, MPa | Ductility $\delta$, % | Hardness HV30, GPa |
|-------------------|-----------------------------|-----------------------------------------------|-----------------------|-------------------|
| Ti+0.5%SiC        | 689                         | 770                                            | 14.3                  | 2.0               |
| Ti+1.5% SiC       | 745                         | 823                                            | 9.4                   | 2.7               |
| Ti+1.5% SiC (CR)  | 927                         | 1038                                           | 7.5                   | -                 |

Heat treatment was carried out to improve the material properties. It was done in a vacuum furnace by heating to 1200°C temperature. Cooling took place together with a furnace at 100°C per hour rate. As can be seen form Table 4, the characteristics of alloys after heat treatment have almost no differences, only insignificant difference in ductility is observed.

| Composition       | Short-term tensile strength limit $\sigma_t$, MPa | Yield limit $\sigma_y$, MPa | Ductility $\delta$, % |
|-------------------|---------------------------------------------------|-----------------------------|-----------------------|
| Ti+0.5% SiC       | 2173                                              | 1515                        | 9.4                   |
| Ti+1.5% SiC       | 2196                                              | 1555                        | 8.6                   |

The obtained alloys were also quenched. Heating was carried out in a resistance furnace to 1100°C temperature. The quenching medium was water of 20°C temperature. Quenching was carried out till hardness increase and considerable decrease of ductility (Table 5).
Table 5. Characteristics of titanium alloys (tensile deformation) after quenching

| Composition   | Short-term tensile strength limit, $\sigma_t$, MPa | Yield limit $\sigma_y$, MPa | Ductility $\delta$, % | Hardness, HRC |
|---------------|--------------------------------------------------|-----------------------------|-----------------------|----------------|
| Ti+0.5%SiC    | 1370                                             | 1250                        | 0.8                   | 44-46          |
| Ti+1.5%SiC    | 1440                                             | 1350                        | 0.6                   | 54-56          |

4. Conclusions
1. In addition of SiC nanosized powder as a modifier the structure of cast titanium after electron beam melting is characterized with high dispersion of grains and uniform distribution of nanosized particles. It is determined that increase of portion of nanosized silicon carbide in titanium results in rise of cast metal hardness.
2. High-temperature plastic deformation of cast titanium ingots after electron beam melting leads to formation of sufficiently high mechanical properties of material.
3. Heat treatment of wrought titanium alloys significantly affects the final mechanical characteristics. Quenching of the obtained metal composites results in considerable increase of strength and significant decrease of ductility. The same effect can be obtained by means of cold rolling due to formation of high dislocation density. The best combination of strength and ductility of metal composite is achieved after heat treatment at 1200°C temperature.

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