УДК 669.45 + 669.046.558

DOI: 10.15421/452113

WAYS TO INCREASE PLASTICITY IN DEFORMATION OF TITANIUM ALLOYS WITH MINIMIZATION OF ENERGY COSTS

S. Polishko

Oles Honchar Dnipro National University, 1st building of DNU, Gagarin Avenue, 72, Dnipro city, 49010, Ukraine

Annotation. This article dial with study, which was carried out to increase the ductility and deformability of titanium alloys BT1-0 and BT6, as well as the formation of highly plastic β-phase emissions in the microvolumes of the alloy. It was determined that the reason for the satisfactory combination of high plastic and impact characteristics with significant strength ($σ_в$> 800 MPa) were the following factors: the formation of a significant amount of metastable β-phase, has high plasticity and favorable morphology of the structure in the form of quasi-eutectoid, in which α -phase alternates with plastic β-layers. Research and experiments based on the new concept have proven the prospects of microalloying titanium with a non-deficient effective alloying element, iron. It also shows the real possibility of using much cheaper low-grade sponge-titanium (compared to high-purity sponge titanium) in the smelting of ingots and their processing with a decrease in energy consumption of processing processes and significant economy of titanium. Analysis of these experimental data allowed us to draw the following conclusions. With an increase in the amount of iron in the alloys of the Ti-Fe system, the yield strength and Brinell hardness naturally increased. As shown, iron "loosens" the crystal lattice of titanium and can't increase the strength of the interatomic bond. Therefore, the nature of the strengthening of titanium iron is different. It is due to the following: grinding of grain in cast and forged states under the influence of iron. It was found that the size of cast grains decreased tenfold during doping titanium alloys by iron. Thus, with increasing concentration of iron in the titanium alloys, the length of the grain boundaries, which were an obstacle to the movement of dislocations, increased sharply.

Keywords: TITANIUM ALLOYS, CHEMICAL COMPOSITION, STRUCTURE, PHASES, MECHANICAL CHARACTERISTICS.

СПОСІБИ ПІДВИЩЕННЯ ПЛАСТИЧНОСТІ ПРИ ДЕФОРМАЦІЇ ТИТАНОВІХ СПЛАВІВ З МІНІМІЗАЦІЄЮ ЕНЕРГОВИТРАТ

С.О. Полішко

Дніпровський національний університет імені Олеся Гончара, пр. Гагаріна, 72, Дніпро, Україна

Анотація. Проведено дослідження з підвищення пластичності і деформованості титанових сплавів ВТ1-0 і ВТ6 та формування високопластичних виділень β-фази в мікрооб'ємах сплаву. Визначено, що причиною задовільного поєднання високих пластичних і ударних властивостей зі значною міцністю ($σ_в$>800 МПа) були такі фактори: формування значної кількості метастабільної β-фази, яка має високу пластичність та сприятлива морфологія структури у вигляді квазіевтектоїду, при якій α-фаза чергується з пластичними β-прошарками. Дослідженнями та експериментами на базі нової концепції доведено перспективність мікролегування титану недефіцитним ефективним легуючим елементом – залізом. Також показано реальну можливість використання значно дешевшого низькосортного губчастого титану (у порівнянні з губчастим титаном високої чистоти) при виплавці зливків та обробці їх зі зниженням енергоємності технологічних процесів обробки і значною економією титану. Аналіз отриманих в статті даних дозволив зробити наступні висновки. Зі збільшенням кількості желе-за в сплавах системи Ti-Fe природно збільшуються границя плинності і твердість за Бринелем. Як показано в статті, залізо «розрихляє» кристалічну решітку титану і не може збільшити міцність міжатомного зв'язку. Тому характер зміцнения титанового заліза різноманітний. Це пов'язано з наступним: змішування зерна у литому і кованому стані під дією Fe. Установлено, що при легуванні титанових сплавів залізом розміром литих зерен зменшився в 10 разів. Таким чином, зі збільшенням концентрації заліза в титанових сплавах довжини кордону зерен, які були перешкодою для руху дислокацій, різко збільшувалися.

Ключові слова: ТИТАНОВІ СПЛАВИ, ХІМІЧНИЙ СКЛАД, СТРУКТУРА, ФАЗИ, МЕХАНІЧНІ ВЛАСТИВОСТІ.

СПОСОБЫ ПОВЫШЕНИЯ ПЛАСТИЧНОСТИ ПРИ ДЕФОРМАЦИИ ТИТАНОВЫХ СПЛАВОВ С МИНИМИЗАЦИЕЙ ЭНЕРГОЗАТРАТ

С.А. Полишко

Днепровский национальный университет имени Олеся Гончара, пр. Гагарина, 72, Днипро, Украина

Аннотация. Проведено исследование по повышению пластичности и деформируемости титановых сплавов ВТ1-0 и ВТ6, а также формирования высокопластичных выделений β-фазы в микрообъёмах сплава. Определено, что причиной удовлетворительного сочетания высоких пластических и ударных свойств со значительной прочностью (σв> 800 МПа) были следующие факторы: формирование значительного количества метастабильной β-фазы, которая обладает высокой пластичностью и благоприятной морфологией структуры в виде квазиевтектоида, при которой α-фаза чередуется с пластическими β-слоями. Исследованиями и экспериментами на базе новой концепции доказана перспективность микролегирования титана недефицитным эффективным легирующим элементом – железом. Также показана реальная возможность использования значительно более дешевого низкосортного губчатого титана (по сравнению с губчатым титаном высокой чистоты) при выплавке слитков и обработке их со снижением энергоемкости технологических процессов обработки и значительной экономией титана. Анализ полученных в статье данных позволил сделать следующие выводы. С увеличением количества железа в сплавах системы Ti-Fe естественно увеличиваются предел текучести и твердость по Бринеллю. Как показано в статье, железо «разрыхляет» кристаллическую решетку титана и не может увеличить прочность межатомной связи. Поэтому характер упрочнения титана железом различен. Это связано со следующим: измельчение зерна в литом и кованом состоянии под действием железа. Установлено, что при легировании титановых сплавов железом размер литых зерен уменьшился в 10 раз. Таким образом, с увеличением концентрации железа в титановых сплавах длина границ зерен, которые были препятствием для движения дислокаций, резко увеличивалась.

Ключевые слова: ТИТАНОВЫЕ СПЛАВЫ, ХИМИЧЕСКИЙ СОСТАВ, СТРУКТУРА, ФАЗЫ, МЕХАНИЧЕСКИЕ СВОЙСТВА.

Introduction

The problem of increasing the ductility of titanium alloys is now more important in the world practice of titanium products. This is due to the following reasons. α- Titanium has a relatively low ductility. It is due to the fact that the α-phase has a hexagonal crystal lattice with a small number of sliding planes. It occurs in α-titanium in prismatic planes { } and only partially along the pyramidal planes { } and on the plane of the base. The implementation of plastic deformation in α -titanium is also possible by twinning. Another phase of titanium, the β-phase, has a cubic volume-centered lattice. It is ductile because it has a large number of sliding planes, like other alloys with a cubic lattice. However, to form the structure of biphasic titanium alloys with a significant volume of β-phase, it is necessary to alloy them with a significant number of β-stabilizers, such as V, Mo, Mn, Fe, Si, Cr or a neutral element, Zr. However, as shown above, some of them have a noticeable solubility not only in the β but also in the α-phase, significantly strengthening it. Therefore, it is necessary to find new solutions that would not only strengthen the α-phase and alloys, but also to form the optimal volume in the structure of the alloy, composition and strength of the β-phase. At the same time, as titanium and its alloys are increasingly used in aerospace, rocketry, submarine engineering, mechanical engineering, nuclear energy, medicine, and the oil industry, the study of its use will be relevant for a long time. In this work, studies to increase the ductility and deformability of titanium alloys VT1-0 and VT6 were performed in the study of the formation of highly plastic β-phase emissions in the microvolumes of the alloy; Previous and last three years of research have shown the possibility of forming a highly plastic β-phase in microvolumes of titanium alloy. The choice of elements of β-stabilizers for micro- and titanium doping was based on three aspects: - β-stabilizing effect of the alloying element; - influence on the characteristics of strength and ductility; - economic feasibility. It is known that iron is a stronger β-stabilizer of titanium. This is caused not only by the large difference in the sizes of Ti and Fe atoms, but also by the electronic configurations of both elements and the electronic structure of the interacting atoms. Titanium and iron are ds-elements in which, when the d-shells are incompletely filled, the s-shells are also filled. Stable configurations of d-electrons are d0, d5, d10 [1, 2].

Formulation of the research problem

Conduct research on Development of Methods of Increasing Plasticity During Deformation of Titanium Alloys With Minimization of Energy Costs Discussion (Problem solving). Titanium has a configuration of valence electrons d2s2, therefore stable configurations in the condensed state are d0, d5, and under normal conditions d0-states predominate. This is confirmed by the fact of high electrical resistance of titanium, which is due to the emergence of strong interelectron interaction. This is manifested in the loosening of the lattice due to the transition in the formation of d0-states of part of the valence electrons to the collectivized state. When iron atoms are introduced into the alloy in addition to titanium as a base, the energy stability of the system as a whole decreases due to a significant increase in the concentration of collectivized electrons, although the statistical weight of stable d5 and d10 states increases under the influence of iron. That is why the introduction of iron into titanium reduces the energy stability of the system of Ti-Fe alloys. In this case, Ti is the donor and Fe is the acceptor.

Solution of the problem

As mentioned above, in addition to the β-stabilizing effect, it was necessary to establish the effect of iron on the structure and mechanical characteristics of titanium. For this purpose, a series of alloys of high-purity spongy titanium having a Brinell hardness from 900 HB to 950 HB with pure Fe powders, which were pressed into a consumable electrode (BE) in the following ratios (Tab. 1), was smelted in a 1.5 kg VDLP furnace.

Since the state of the alloy (cast, forged, rolled) can have a significant impact on the formation of phases, microstructure, characteristics, all Ti-Fe alloys were forged on bars with a diameter of 0.02 m, relieved stress by annealing at 700 ºC for 0.5 h. Then the alpha layer 1 mm deep was removed, the rod was cut into samples for the study of mechanical characteristics (five samples for tensile tests and three samples for toughness). Sections were made from the heads of bursting samples, the composition of the phases was also determined on them.

Table 1 – Titanium alloys chemical composition

Alloy (for charge)	Composition Fe, %	Impurities, %			
		O	N	C	H
Ti-0,1 Fe	0,11	0,09	0,03	0,012	0,005
Ti-0,3 Fe	0,33	0,10	0,03	0,013	0,003
Ti-0,5 Fe	0,48	0,08	0,02	0,014	0,004
Ti-0,7 Fe	0,73	0,06	0,03	0,012	0,003
Ti-1,0 Fe	1,02	0,08	0,02	0,015	0,004
Ti-1,5 Fe	1,56	0,10	0,02	0,011	0,004
Ti-2,0 Fe	2,42	0,11	0,03	0,013	0,004
Ti-3,0 Fe	3,03	0,09	0,03	0,013	0,005
Ti-4,0 Fe	4,10	0,10	0,04	0,012	0,004
Ti-5,0 Fe	5,04	0,08	0,03	0,011	0,004
Ti-6,0 Fe	5,90	0,07	0,03	0,010	0,003

Dependencies are established:

- increase in the yield strength and Brinell hardness of forged samples of Ti-Fe alloys (Fig.1) with increasing iron content;

- changes in relative elongation, relative narrowing and toughness with increasing concentration of iron in Ti-Fe alloys (Fig.2);

increasing the amount of β-phase with increasing concentration of iron in cast and forged samples of Ti-Fe alloys (Fig.3)

- increasing the tensile strength of Ti-Fe alloys with increasing the amount of β-phase in them (Fig.4);

- the relationship between the relative narrowing and the amount of β-phase in the structure of Ti-Fe alloys (Fig.5).

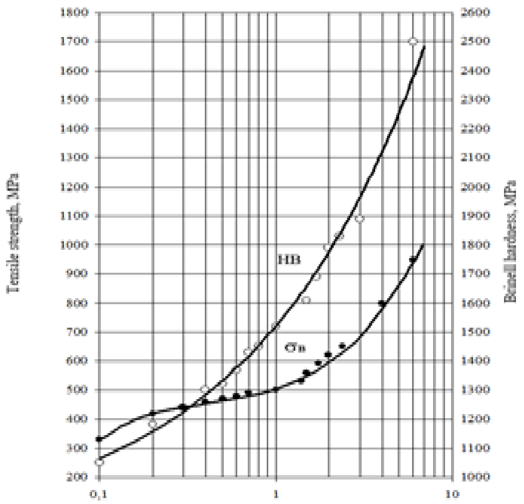

Figure 1 - Increasing the tensile strength and hardness of forged samples of Ti-Fe alloys depending on the concentration of Fe

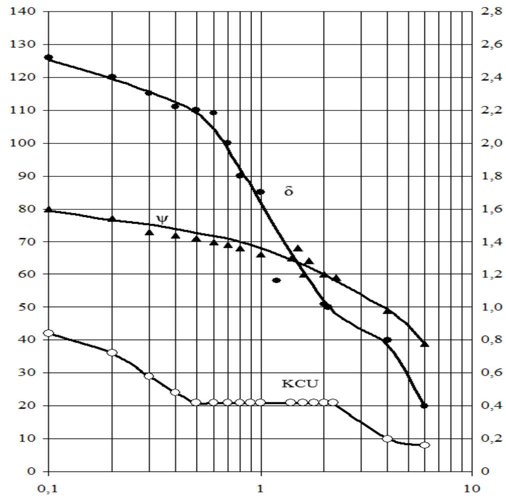

Figure 2 - Dependence of relative elongation, relative narrowing and toughness on the concentration of iron samples of forged Ti-Fe alloys

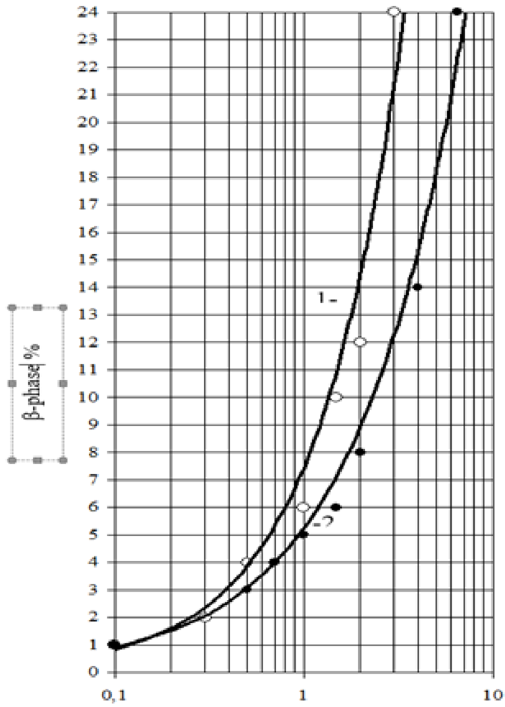

Figure 3 - Dependence of the amount of β-phase on the concentration of iron in cast (1) and forged (2) samples of Ti-Fe alloys

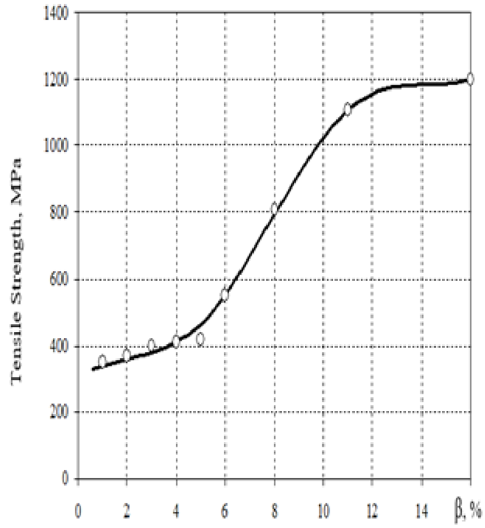

Figure 4 - Increasing the tensile strength of Ti-Fe alloys depending on the amount of β-phase in their structure

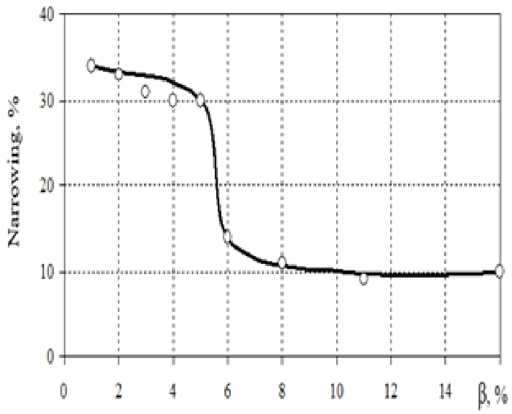

Figure 5 - Change in the relative elongation of Ti-Fe alloys depending on the amount of β-phase in their structure

Table 2 presents data on the change in the phase composition of Ti-Fe alloys with increasing iron concentration according to the results of X-ray phase analysis.

The tensile strength indices σв and HB increased accordingly. Thus, the mechanism of grain boundary strengthening was very significant; increasing the dispersion of the structure under the action of iron. Already in alloys containing 0.3% Fe formed a quasi-eutectoid structure α + β metastab. We have proved that the decay of the β-phase during cooling of Ti-Fe alloys did not occur in accordance with the equilibrium diagram of Ti-Fe, according to which eutectoid decay must follow the reaction: βevt → α + TiFe. In reality, the decay of the β-phase developed by a different mechanism: βevt → α + βmetastab. The peculiarity of this decay is the fact that the quasi-eutectoid appears at much lower concentrations of iron than could be expected from the state diagram of Ti-Fe. This is due to the difficulty of diffusion processes at eutectoid temperature for the following reasons:

1) low temperature of eutectoid decay (590 ºC);

2) low values of the parameters of diffusion of iron in titanium, which occurs in a solid solution of substitution;

3) significant micro-distortion of the crystal lattice due to the size factor;

4) high density of valence electrons, which increased under the influence of iron. The β-phase layers, which were isolated as a quasi-eutectoid, are a significant obstacle to the movement of dislocations, strengthening the alloy by the mechanism of "reinforcement";

5) a large difference in the sizes of Ti and Fe atoms, which causes micro-distortion of the titanium crystal lattice, which hinders the movement of dislocations and increases the strength of Ti-Fe alloys.

Table 2 - Phase composition and change in the amount of β-phase according to X-ray phase analysis

Alloy	Cast condition		Forging + annealing 700 ºC	
	phase	β-phase	phase	β-phase
Ti+0,1 % Fe	α, β	1,0	α, β	1,0
Ti+0,3 % Fe	α, β	2,0	α, β	2.0
Ti+0,5 % Fe	α, β	3,0	α, β	3,0
Ti+0,7 % Fe	α, β	4,0	α, β	4,0
Ti+1,0 % Fe	α, β	6,0	α, β	5,0
Ti+1,5 % Fe	α, β	10,0	α, β	6,0
Ti+2,0 % Fe	α, β	13,0	α, β	8,0
Ti+3,0 % Fe	α, β	17,0	α, β	11,0
Ti+4,0 % Fe	α, β	24,0	α, β	14,0
Ti+5,0 % Fe	α, β	28,0	α, β	16,0

At the same time, in terms of absolute value, the characteristics of ductility (δ, ψ) and toughness, despite a significant increase in strength and hardness, remained quite high - elongation at 20% even at an iron content of 1.4%, relative narrowing was 30%, toughness - 0.8 MJ / m2. This concentration of iron corresponded to the values of strength σв> 800 MPa and hardness of 2100 HB, the amount of β-phase from 10 to 12%. The reason for the satisfactory combination of high plastic and impact characteristics with significant strength (σв> 800 MPa) were the following factors:

- formation of a significant amount of metastable β-phase, which has high plasticity;
- favorable morphology of the structure in the form of a quasi-eutectoid, in which the α-phase alternates with plastic β-layers.

Therefore, it is possible to increase the ductility of titanium alloys by forming highly plastic β-layers in the metal structure. Since α-titanium already at an iron content of 0.3% may form them in a significant amount (> 0.2%), its introduction into titanium alloys and the corresponding processing of such alloys (deformation + heat processing) under the new modes can increase the deformability of alloys. Due to the high iron content, the titanium alloy can be deformed at lower temperatures, because iron significantly reduces the temperature range of the β-phase (up to t <590 ºC). We have made assumptions about the possibility of using low-grade spongy titanium as a charge in the smelting of titanium alloy with high iron content with the addition of substandard waste. Spongy titanium for smelting an experimental ingot with a high iron content was taken from the contaminated metal of the bottoms of the titanium block. For this purpose, the coarse laboratory ingot was first smelted in a vacuum-arc method with double remelting. Its chemical composition is given in fig. 6.

The ingot was forged on a billet for rolling and on a semi-industrial state duo "210" was rolled from one heating (890 ºC) with a total compression of 80% when transferring the roll manually through the upper roll. A similar workpiece was deformed in the same state by hot rolling (from 600 to 700 ºC) with ε = 69% for six passes to a sheet thickness of 5 mm. After annealing in air at 700 ºC for 0.5 h, the sheet was subjected to alkaline-acid etching followed by short-term (0.5 h) vacuum annealing. The mechanical characteristics of titanium alloy with high iron and oxygen content are given in fig.7.

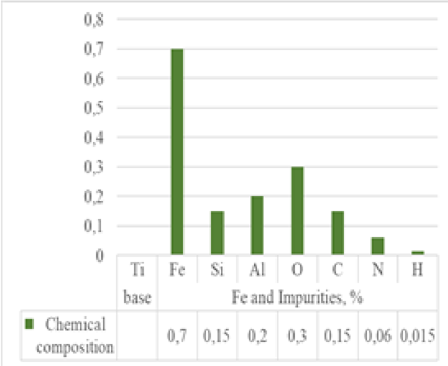

Figure 6 – Chemical composition of the experimental ingot

In the process of hot, warm and even cold rolling (with a total deformation of 77.5% for four passes with one intermediate annealing at 700 ºC for 0.5 h) the alloy showed an excellent ability to deform due to the presence in its structure from 4 to 5% highly ductile β-phase in the form of layers between α-plates.

The mechanical properties of the Ti-0.7Fe alloy were at the level of doped Al and Mn pseudo α-alloy OT4-1 (σв - 680 MPa, σт - 500 MPa, δ - 15%).

One of the blanks was rolled first by warm and then cold rolling with intermediate heating to 700 ºC for 0.5 h in foil 0.12 mm thick.

Previous semi-industrial experiments allowed to realize industrial smelting of ingots weighing 0.7 tons by double vacuum-arc remelting, forging and rolling by standard technologies into rods with a diameter of 0.02, 0.04 and 0.06 m and sheets with a thickness of 5 mm. The chemical composition of ingots is given in Fig 8.

The mechanical properties of rods with a diameter of 0.02 mm in comparison with the characteristics of technical titanium brand VT1-0 mass production are if fig. 9.

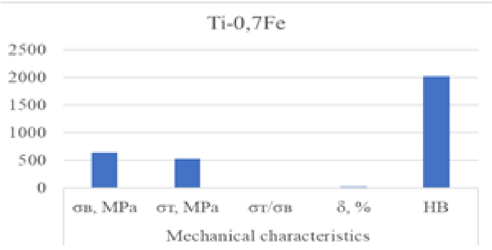

Figure 7 - Mechanical characteristics of titanium alloy Ti-0.7Fe after hot rolling and annealing

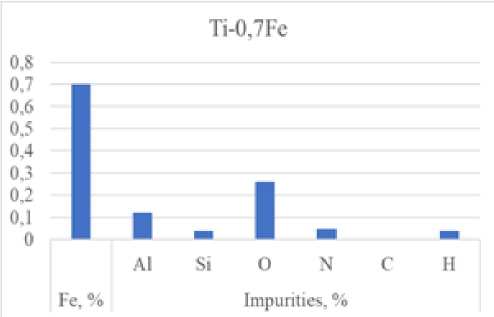

Figure 8 - Chemical composition of the industrial alloy Ti-0,7Fe

Rolling ingot from Ti-0,7Fe alloy was performed at lower temperatures (beginning at 1000 ºC instead of 1050 ºC, ending at 700 ºC instead of 750 ºC). The difference of 50 ºC when heated gives significant energy savings. It is established that the high ductility of the industrial alloy Ti-0.7Fe is due to the formation of highly plastic β-layers enriched in iron (Fig.10).

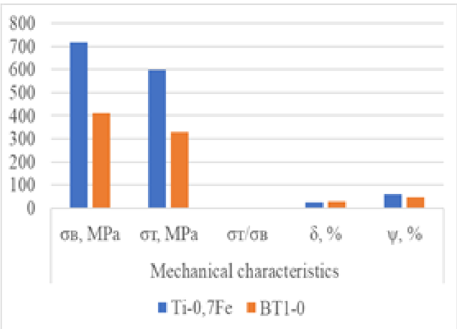

Figure 9 - Mechanical properties of bars of alloys Ti-0,7Fe and VT1-0

Figure 10 - Microstructure of rolled industrial sample ingot of Ti-0,7Fe alloy with β-layers between α-plates, x2000

Numerical experiments with testing of high ductility and deformability of alloys doped with iron allowed to protect Ti-Fe alloys with security documents [3]. To increase the corrosion resistance of Ti-Fe alloys, they were additionally microalloyed [4].

Research and experiments based on the new concept have proven the viability of titanium microalloying with a non-deficient effective alloying element, iron. It also shows the real possibility of using much cheaper low-grade spongy titanium (compared to high-purity spongy titanium) in the smelting of ingots and their processing with reduced energy consumption of processing processes and significant savings of titanium [5].

Scientific novelty

The main scientific novelty of the research results, technologies for production and processing of titanium alloys VT1-0 and VT6 (EPPE) was as follows:

- smelting of massive (2.2 and 1.1 tons) EPPE ingots by the method of JSC "Electron Beam Metallurgy Plant" from one remelting;

- obtaining high-purity alloys for impurities with a homogeneous fine-grained macrostructure and a microstructure of high dispersion, with shifted critical points of phase transitions towards lower temperatures;

- increase the ductility of both alloys by 24% and significantly improve the deformability of alloys;

- creation of an original scheme of pressure processing of large massive ingots of alloys VT1-0 and VT6 on the existing equipment for deformation of ferrous metals in two different industries;

- development of energy- and resource-saving temperature-time regimes and technologies of deformation and heat processing, which provided higher mechanical properties (σв, δ, ψ, KCU) of finished products from two titanium alloys of electron beam smelting in comparison with serial alloys of vacuum-arc remelting.

Conclusions

Analysis of these experimental data allowed us to draw the following conclusions.

With an increase in the amount of iron in the alloys of the Ti-Fe system, the yield strength and Brinell hardness naturally increased.

As shown above, iron "loosens" the crystal lattice of titanium and can not increase the strength of the interatomic bond. Therefore, the nature of the strengthening of titanium iron is different. It is due to the following:

- grinding of grain in cast and forged states under the influence of iron. It was found that the size of cast grains decreased tenfold during doping titanium iron. Thus, with increasing concentration of iron in titanium, the length of the grain boundaries, which were an obstacle to the movement of dislocations, increased sharply.

The development of modes of heating under deformation and heat processing is carried out taking into account comprehensive research on gas saturation of compact titanium and titanium powders of different production methods.

Bibliographic references

1. Самсонов Г.В. Конфигурационная модель вещества. - Киев: Изд-во Наукова думка, 1971. 315 с.
2. Корнилов И. И. Титан. - М.: Наука, 1975. 306 с.
3. Деклараційний патент 71466 А Україна, МПК С22С14/00 Титановий сплав / О.М. Шаповалова, О.В. Шаповалов, Т.І Івченко. Опубл.15.11.2004 // Бюл. № 11.
4. Патон Б.Е. Электронно-лучевая плавка. – К.: Изд-во Наукова думка, 1997. 263 с.
5. Теоретичні основи керованого структуроутворення сплавів для підвищення їх властивостей шляхом бробки розплавів спеціальними модифікаторами з енергозбереженням: отчет по НИР (заключ.) // кер. Санін А. Ф., вик. Івченко Т .І., Бабенко О. П., Кушнір М. А., Маркова І. А., Полішко С. О., Татарко Ю. В.– Дніпропетровськ, 2013. 115 с.№ ДР 0111U001143, № 6-243-11.

Надійшла до редколегії 29.03.2021

Authors information

Serhii Polishko, Ukraine
Oles Honchar Dnipro National University.
Associate Professor of Manufacturing Technology, PhD, Senior Researcher.
Area of interest - steels and alloys modification