INVESTIGATION OF VARIOUS METHODS OF MELTING AND CASTING OF TITANIUM ALLOYS

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The method of double vacuum arc consumable-electrode melting is most widely used in production of ingots of wrought titanium alloys. By combining the melting of electrode and ingot formation a maximum simplicity is achieved in the melting furnace design, thus providing for its high reliability. This method, however, proved to be not enough efficient in solving the following main problems:

1. Necessity of sharp increase of the portion of return waste materials and scrap involved in the charge, including the organization of the closed metallurgical balance when producing titanium-alloy parts.

2. Improving the chemical homogeneity of the ingots, primarily those of complex alloys and complete removal of defects in the form of inclusions and local macroinhomogeneity zones.

3. Preparation of the billets of optimum shape and size for their further plastic working.

An evaluation is given in the present study of various methods of melting and casting from the viewpoint of solving the problems, mentioned above.
All the methods of melting and casting known as applied to titanium alloys may be subdivided into three main modes:

- melting and ingot formation is accomplished in a water-cooled mould;
- melting proceeds in a skull crucible with subsequent pouring metal into a mould at a high rate;
- metal is melted in some intermediate vessel, from which it periodically or continuously flows down to the mould.

The charge materials may be fed into a melting zone either in the form of consumable electrode or in the form of the bulk charge including both primary metals (titanium sponge and alloying components) and scrap. The decrease in mechanical strength of the extruded electrode with increasing portion of the waste materials (especially lump ones) in the charge restricts their usage and requires refinement down to dimensions several times less than diameter of consumable electrode thus considerably increasing the labour consumption in preparing the raw material for melting and leads to considerable metal losses.

When introducing the bulk charge into the melting zone an arbitrary portion of the scrap in it may be chosen depending upon the oxygen and nitrogen content in the charge materials and respective specifications for those elements in the ingot.

The charge may be melted either by an independent heating source (plasma-arc, electron beam, etc.) [1, 2, 3], or by the arc using the skull as consumable electrode [4].

If melting is accomplished in a mould or in some intermediate vessel, then scrap is prepared practically in the same way as it is done in the case of the extruded consumable electrode. When melting proceeds in a crucible, then in a charge
there may be used lump scrap of considerably larger size (up to 1000 mm for commercial furnaces).

The best chemical homogeneity of the ingots, determined by the methods of their preparation, may be also achieved when melting in a crucible since in this case all the metal, destined to form an ingot is molten before pouring. When melting in an intermediate vessel this condition is not fulfilled. Since the portions of the melt, which are fed to a mould can significantly vary in chemical composition then relationship between the weight of the liquid bath in a solidifying ingot and that of the melt portion should be fulfilled at any moment of the melting in order to prepare the ingot of a given chemical homogeneity. This relationship is determined by how much the true composition of the portion differs from that of calculated one.

When running the process is correct, then melting in both crucible and intermediate vessel ensures the absence of solid pieces of the charge, which can lead to formation of defects in the form of inclusions and local macroinhomogeneity zones in the ingot.

When the bulk charge is melted which is charged into a mould step-by-step, then the least possibility exists to prepare a chemically homogeneous ingot, since only part of the ingot is melted at any moment of time, while solid particles of the charge, having higher density and melting point than those of the base metal, may form defects in a solidifying ingot.

Thus skull melting is the best one of the methods known nowadays to solve the problems of more complete usage of return scrap and preparation of chemically homogeneous ingots.

Of two modes of the skull melting — the first one using an independent heating source and the second one — with consumable electrode-skull — the latter is more suitable from technological and power consumption points of view (Fig. 1).
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Fig. 1 Relative specific consumption of electric power when melting the ingots in skull-furnaces with different heat-sources:
1 - vacuum arc using the skull as a consumable electrode;
2 - electron-beam;
3 - plasma-arc and nonconsumable-electrode melting.

In the course of long-term tests under industrial conditions of the skull-melting technique with the skull used as consumable electrode, high chemical homogeneity is established of the ingots including those of high alloys containing up to 50% of alloying elements in the charge, their melting temperature ranging from 2320°C up to 2600°C. The method proved to be also effective to introduce the scrap in the charge, including those being coarse lump. Thereby the portion of the scrap in the charge is not restricted by the means of its introduction.
When combining the estimation of possibility to produce ingots and that of requirements to initial billets for manufacturing semi-products the conclusion can be made that cylindrical ingots-billets 100 to 300 mm in dia. and ingots-slabs of rectangular cross-section are the optimum ones.

The main criterion to choose the method of the ingots-billets production is the ingot quality, determined by solidification parameters, which in turn depend upon casting rate, ingot dimensions and cooling intensity of its side surface. At too high rates of casting the voids of shrinkage nature are formed in the axial zone of the ingot.

Fig. 2 shows limit values of casting rate for low and medium titanium alloys. Increasing the intensity of the ingot side surface cooling is accomplished by increasing the upper limit of the casting rate. The estimation of the acceptable values is given in Fig. 2, calculated under conditions of keeping the ingot side surface temperature at a zero level (Bimol).

The upper limit of the casting rate is lower for high titanium alloys than those given in Fig. 2, since the local ingot segregation takes place in the form of the «cords» and freckles of different etchability. The lower limit of the casting rate determined as that required to keep the metal liquid on its way to the mould, depends on the distance between the crucible and the mould as well as upon the intensity of heating or cooling the melt.

Calculations and experience show that requirements to the upper and lower limits of the casting rate prove to be incompatible under real conditions, when the pouring metal is not heated with additional heaters. When the melt is additionally heated during the pouring then casting rate may be controlled over a wide range, and conditions necessary to prepare ingots of high
quality will be satisfied.

Fig. 2 Change of the limiting rate of casting depending upon the ingot diameter under solidification in vacuum (1) and at infinitely high rate of cooling (2).

The pouring with additional heating may be practically done in both the melting of consumable electrode in a mould and during the melting in a skull crucible or intermediate vessel.
Since melting in a mould of cylindrical ingots-billets 100-300 mm in dia. as well as ingots of rectangular section using consumable electrode is not effective on a commercial scale, while large amount of melted metal should be kept liquid for a long time when controlling the rate of casting from the skull crucible, then melting consumable electrode in an intermediate vessel followed by pouring the melt into a mould with the cross-section required, proved to be the best method to prepare the ingots-billets.

The electroslag melting provides for even heating of the melt flowing down to a mould as well as that of the upper part of the metal bath. The melting of consumable electrode is carried out at a given rate, changing proportionally to the power supply.

The casting rate allowable with respect to withdrawal conditions is several times as much as rates achieved in vacuum-arc, electron-beam and plasma-arc methods of melting into a D. C. mould (Fig. 3).

![Fig. 3](image)

Fig. 3 The casting rates achieved when melting ingots 120 mm in dia. into D. C. mould:
1 - vacuum-arc and electron-beam melting;
2 - plasma-arc melting;
3 - electroslag melting.
When pulling-out the ingots 120 mm and over in dia. at the rates exceeding 100 mm/min the discontinuities are revealed in the surface skin of ingots, through which the melt is pouring. The surface of ingots prepared under optimum conditions is sufficiently smooth, free of the slag skin and practically no mechanical treatment is required before the deformation which follows.

It is noteworthy, that casting rates, providing for high quality of the ingots surface, do not exceed the permissible values of this parameter established according to conditions determining the preparation of a dense ingot (see Fig. 2) even under conditions of cooling in a vacuum.

The isotope technique was used to investigate the structure of ingots of Ti-6.2%; Al-2.4%; Mo-1.5%; Cr-0.5%; Fe-0.3% alloy. W-185 was introduced into consumable electrodes, which were then melted using the electroslag method in an intermediate vessel, from which the melt was fed to the mould. As a slag, chemically pure CaF was used.

The autoradiograms obtained indicate the crystallization, which is mostly of the cell type, except the metal pool, solidifying at the last moment (Fig. 4)

The ingots macrostructure is of columnar type. At the melting rate of 60 mm/min a zone appears along the ingot axis of equiaxial grains, thereby no voids of any kind were observed.

At the same reduction the mechanical properties of the electroslag metal are distinguished by their higher uniformity (see Table) as compared to those of the rods, prepared from ingots 370 mm in dia. of vacuum-arc melting.

* The investigations were carried out together with V. P. Kuraev and G. M. Rakovshchik.
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Fig. 4 Macrostructure (a) and autoradiogramme (b) of the ingot 120 mm in dia. obtained by electroslag melting at the rate of 60 mm/min.

Conclusions

The analysis carried out has shown the flow sheet including the primary skull melting with the skull as consumable electrode followed by electroslag remelting in an intermediate vessel with further pouring metal into a mould of the cross-section required to be the most effective technological scheme in improving the metal quality in the stage of ingot preparation as well as improving conditions of its usage.

The process of primary melting is succeeded in solving the problems dealing with introduction of the scrap into the bulk charge as well as preparation of the ingots chemically pure over the macrovolumes with practically no inclusions guaranteed, while secondary melting and pouring provides for preparation of dense ingots-billets of the shape and dimensions required.
### Table

#### Mechanical properties of deformed metal

<table>
<thead>
<tr>
<th>Methods of ingot melting</th>
<th>Composition</th>
<th>UTS $\text{kgf/mm}^2$</th>
<th>YS $\text{kgf/mm}^2$</th>
<th>El.</th>
<th>RA</th>
<th>Impact strength $\text{kgf/m/cm}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electroslag (diameter of 120 mm)</td>
<td>Al - 6.2</td>
<td>112</td>
<td>109</td>
<td>13.1</td>
<td>48.2</td>
<td>4.6</td>
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<tr>
<td></td>
<td>Mo - 2.3</td>
<td>Si - 0.27</td>
<td>1.9</td>
<td>2.0</td>
<td>1.1</td>
<td>2.8</td>
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<tr>
<td></td>
<td>Cr - 1.4</td>
<td>O$_2$ - 0.09</td>
<td>1.9</td>
<td>2.0</td>
<td>1.1</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>Fe - 0.4</td>
<td>H$_2$ - 0.003</td>
<td>2.8</td>
<td>0.3</td>
<td>2.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Vacuum-arc (diameter of 370 mm)</td>
<td>Al - 6.5</td>
<td>112</td>
<td>114</td>
<td>15.9</td>
<td>41.9</td>
<td>5.12</td>
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<tr>
<td></td>
<td>Mo - 2.4</td>
<td>O$_2$ - 0.10</td>
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<tr>
<td></td>
<td>Cr - 1.9</td>
<td>H$_2$ - 0.002</td>
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<tr>
<td></td>
<td>Fe - 0.41</td>
<td>Si - 0.29</td>
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<td>2.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Note - numerator - arithmetic mean
denominator - standard deviation

