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PHYSICAL MODEL OF W AND Ti COMPOUND DURING HOT VACUUM ROLLING IN THE SOLID PHASE

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The paper considers alternative methods for protecting metal surfaces from corrosion-erosion destruction (CED), based on galvanization or on the use of an oxide film. Their advantages and disadvantages are noted. For the manufacture of CED-resistant tungsten targets, which are used in the subcritical assembly created at the NSC KIPT, it is proposed to use the method of vacuum rolling of W and Ti. A layer of Ti serves as a protective coating. To describe the process of combining these metals, a model description is proposed, which is based on the use of the Rayleigh-Taylor dissipative instability theory (DRTI). An estimate of the values of the parameters of a binary metal system subjected to DRTI is given. The obtained characteristic bonding time of dissimilar metals corresponds to that observed in experiments.

INTRODUCTION

In a number of technological processes, it is necessary to use metal structures that can withstand such external factors as: aggressive environments; high temperatures; elevated pressures, corpuscular flows and electromagnetic radiation, as well as mechanical effects (abrasion, bending, wear, etc.). Under such conditions, metal structures are subject to corrosion, accompanied by degradation under the influence of the external environment, or, to a lesser extent, erosion, accompanied by destruction due to mechanical influences [1].

As a rule, electrochemical corrosion is observed in aqueous media, since it proceeds in solutions – electrolytes. Erosive destruction is inherent in metal structures that come into contact and are washed by water flows.

For the course of metal corrosion processes, the following factors are of great importance: type of metal; homogeneity of its bulk structure; surface cleanliness; the magnitude of the electrode potential and the ability of the metal to passivate. The passivation of metals, i.e., the slowing down of the corrosion process, is caused by a change in the metal surface during the formation of oxide films on it. The possibility of passivation depends on the nature of the metal [1]. Metals such as aluminum, titanium, tantalum, tungsten, nickel, chromium and other metals are very easy to passivate.

From the above list of metals, let us dwell on the consideration of the corrosion-erosion properties of W as the most suitable candidate for the manufacture of targets for the NSC KIPT subcritical assembly [2]. As follows from [2], subcritical assembly targets are plates in the form of rectangular prisms made of W, the thickness of which is much less than equal length and width.

However, it is known that W has poor corrosion resistance with respect to aqueous coolants due to the formation of a WO_3 oxide film on the surface with a continuity of $S_W = 3.35$. It is known that at a continuity of $S_{Me} > 2.5$, the protective properties of the film deteriorate as a result of an increase in internal stresses and, as a consequence, its swelling and peeling [3].

Thus, the use of an oxide film *W* does not provide protection against corrosion-erosion destruction of the material.

In addition, W is characterized by high susceptibility to radiation embrittlement [4, 5], which also does not contribute to maintaining the integrity of the material.

Therefore, to use W as targets in a subcritical assembly bathed in an aqueous coolant and exposed to high-energy electron flows, it is necessary to find ways to ensure their corrosion-erosion resistance.

One of the approaches to impart corrosion and erosion resistance to W can be the use of galvanic deposition of cladding coatings from various metals. Ti and Ta can be chosen as such metals, which are also corrosion resistant, but less brittle compared to W. Such coatings are good for providing erosion resistance of large and small (end) areas of metal plates.

However, the galvanization technology is characterized by a multi-stage process, special requirements for cladding metals, thorough surface preparation, and requires long process times. Electroplated coatings, depending on the operating conditions of the part [6], have a thickness of 0.1…60 μm are characterized by low adhesive strength (does not exceed the tensile strength of the least durable metal), as well as inhomogeneity in thickness (arises due to the presence of sharp corners and edges parts closest to the anode).

Thus, galvanization is also of little use for ensuring the corrosion-erosion resistance W of the plates.

The most suitable method for ensuring the corrosion and erosion resistance W of plates is the method of joining dissimilar metals in the solid phase by hot vacuum rolling (HVR) [2]. This method makes it possible to eliminate the disadvantages of galvanic coatings noted above. For example, the adhesion strength of an electrolytic iron coating with mild steel (steel 10) is about 280…300 MPa [7].

On the other hand, in the case of HVR, the strength of the joint W (ultimate strength 1200 MPa [8]) and, for example, a thin layer of Ti (ultimate strength 600 MPa [8]) or Ta (ultimate strength 470 MPa [9]) is determined by the value that exceeds the ultimate strength of a less durable metal [10].

For a comparative assessment of the strength of the connection of dissimilar metals, we consider the galvanic and HVR methods of connection. It follows from the conclusions [10] that the value of the strength of the interface between iron (ultimate strength 250 MPa [8]) and steel 10 (ultimate strength 340 MPa [11]) is less than 340 MPa. This value exceeds the ultimate strength of the galvanic connection of such metals [7].

This paper proposes a physical model for describing the formation conditions and estimating the parameters of the target of the NSC KIPT subcritical assembly created by the W and Ti HVR.

EXPERIMENTAL DATA AND MODEL DESCRIPTION OF W AND Ti COMPOUND BY ROLLING IN VACUUM

The model of joining W and Ti by rolling in vacuum was formulate for the experimental setup and experimental conditions, which are describe in [2].

In this work, the joining of Ta-Ti-W-Ti-Ta by hot rolling in vacuum is carried out in two stages. Heating of the package in the furnace up to 1300 ^{0}C with a holding time of about 1 h and feeding the package under the rolls.

At the first stage of rolling, rolls move a strong Nb alloy mandrel, in which Ta-Ti-W-Ti-Ta layers are packed rigidly and symmetrically with respect to the tungsten layer. The movement of the mandrel is carried out in the forward, reverse and again in the forward direction. Rolling ends when the rolls are in the middle of the mandrel. This stage will be called **dynamic**.

In the second stage of rolling, the rolls remain in a position in the middle of the mandrel, and this state is maintained for several hours. This stage of rolling will be called **static**.

The experimental conditions indicate the absence of relative motion of the rolled metals: a strong mandrel does not allow the metals to move relative to each other. However, it transmits the force of the rolls in the direction transverse to the speed of movement of the metals. Due to the high pressures and rather high temperature of the samples, small volumes of Ti can pass into a quasi-liquid state [12], while the Nb alloy, tantalum, and tungsten remain in the solid phase. This assertion will be supported by estimates below.

In the microscopic dimension, a schematic representation of the interface between W and Ti after the dynamic stage (at the beginning of the static phase) can be represented as shown in Fig. 1.

From Fig. 1 follows, apparently, at the dynamic stage of rolling, protrusions W penetrate into the quasi-liquid Ti, while depressions in W remain unfilled.

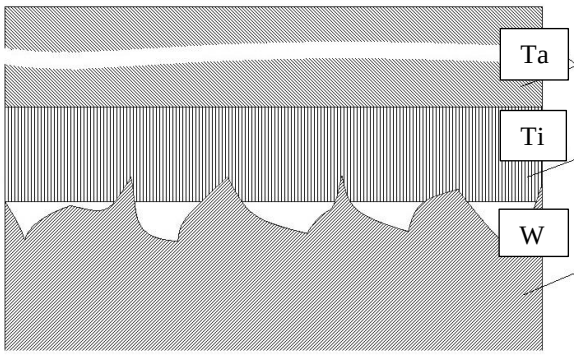

Fig. 1. Scheme of the arrangement of rolled metals at the beginning of the static phase. Vacuum cavities formed by depressions in the tungsten relief are shown at the interface between the tungsten sample and the titanium plate

PHYSICAL MODEL FOR THE DESCRIPTION OF THE W AND Ti HVR PROCESS AT THE STATIC STAGE

At the static stage Ti penetrates into microdepressions in W and the surface of Ti and W joins along the entire interface. Let us consider in more detail this process of joining metals.

We will assume that, in view of the quasi-liquid state of Ti, the process of joining metals occurs as a result of the penetration of Ti into the irregularities of the tungsten boundary. Since the irregularities of tungsten are filled with rarefied air (vacuum), the joining process will be associated with the penetration of a heavier substance (quasi-liquid Ti) into a lighter substance (vacuum). The whole system is placed in a force field, the effective acceleration of which g* is determined by the force of volumetric compression Ti with the Ta + Nb alloy on the one hand, and W – on the other, due to different coefficients of their thermal expansion.

Thus, generalizing the above scheme of joining metals, we arrive at the Rayleigh-Taylor instability problem, which describes the motion of the interface between contacting media located in a gravitational [13] or other force field. In media with dissipation, which is the viscosity of media, such instabilities are called dissipative Rayleigh-Taylor instabilities (DRTI) [14].

To describe the connection of Ti with tungsten, we will consider the process to be completed when Ti fills the irregularities of tungsten. Therefore, to describe such a connection process, we will assume that a heavier, incompressible quasi-liquid – Ti with a density ρ_1 and dynamic viscosity μ_1 borders on a less heavy incompressible liquid – rarefied air, density ρ_2 and dynamic viscosity μ_2. The unperturbed interface coincides with the plane z=0. The heavier liquid is indicated by index 1 and is located in the region z>0.

On Fig. 2 shows a schematic representation of the location of the contacting media, the boundary between which is subject to DRTI.

Under the compressive stress of the rolls, the boundary of Ti, which is in the liquid state, is subjected to the action of surface tension forces and effective acceleration. Under certain conditions, it can be unstable as a result of the development of DRTI [14].

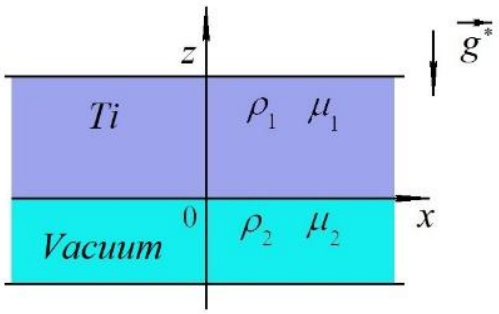

Fig. 2. Schematic representation of the location of the contacting media, the boundary between which is subject to DRTI

Let us estimate the characteristic parameters of the media and determine the conditions for the development of such instability.

The dependence of the boundary deviation amplitude Ti from the equilibrium position on time *t* has the form [14]: $a = a_0\, exp\left(\Lambda \cdot \left(\frac{t}{t_0}\right)\right)$, where a_0 – small deviation of the boundary from the equilibrium position; Λ – dimensionless instability increment; t_0 – characteristic time of the considered system.

The DRTI increment is determined from the equation [14]:

$$\Lambda^2 + 2\Lambda q^2\mu^* - sign(\rho_1 - \rho_2)q + q^3 = 0, \qquad (1)$$

where $\Lambda = \lambda t_0, q = kl_0, \mu^* = \frac{(\mu_1+\mu_2)t_0}{(\rho_2+\rho_1)l_0^2}$, $l_0 = \sqrt{\frac{\sigma}{g^*|\rho_1-\rho_2|}}$, $t_0 = \sqrt{\frac{(\rho_1+\rho_2)l_0}{g^*|\rho_1-\rho_2|}}$. $k = \frac{2\pi}{L}$ – wave number; L – perturbation wavelength; σ – surface tension coefficient Ti in the quasi-liquid state.

If we put $\rho_1 > \rho_2$ in (1), then the DRTI increment is determined by the expression $\Lambda(q) = \sqrt{q^4\mu^{*2} + q - q^3} - q^2\mu^*$, from which it follows that perturbations of the interface, just as in the absence of viscosity, occur for wavelengths in the interval $0 < q < 1$.

On Fig. 3 shows the dependence of the increment of instability of the interface between media $\Lambda(q)$ on the dimensionless wave number q for different values of the dimensionless viscosity μ^*.

From Fig. 3 it follows that with an increase in the dimensionless viscosity μ^*, the maximum value of the growth rate decreases and shifts to the long-wavelength part of the perturbation spectrum.

From expression (1), we estimate the time of joining the boundary Ti + W.

To do this, we use the layout of the metals to be joined and indicate their characteristic thickness Ta – 250 μm; Ti – 30…50 μm; W – (2.5…9.5)·10^{-3} m.

During rolling the compression force of the samples was created by the pressure of the rolls up to 40 Ts on the area of contact with the mandrel made of Nb alloy (the outer area of the upper and lower mandrels is 100×100 mm, the thickness is 20 mm), between which there was a layer of metals Ta+Ti+W+Ti+Ta (see Fig. 1).

At an average pressure of the rolls of 4 Ts, the compression force *Ti* during rolling can be estimated by the value $P_{Ti} \approx \frac{4\cdot10^3 \text{ kg}}{4.4\cdot10^{-3}\, m^2} = \frac{4\cdot10^3\cdot 9.8\cdot \text{ kg·m}/s^2}{4.4\cdot10^{-3} m^2} \approx 8.9$ MPa.

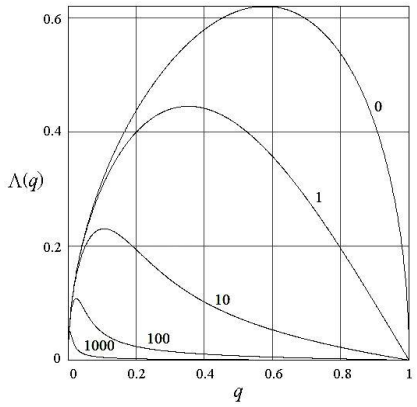

Fig. 3. Dependence of the dimensionless increment of the DRTI of the boundary Ti – Λ(q) on the dimensionless wave number q for different values of the dimensionless viscosity: μ=0; 1; 10; 100; 1000*

It can be seen from the above estimate that, under experimental conditions, the stress created by the rolls exceeds the yield strength of Ti ~ 5 MPa, but is less than the yield strength of the Nb alloy (~18 MPa) [15–17].

At such a pressure and temperature, a thin layer of Ti can pass into a quasi-liquid state [12] and can form a boundary with tungsten, a simplified view of which is shown in Fig. 1.

In the static stage, the mandrel and hard metals are cooled and reduced in size. Under such conditions, after the redistribution and balancing of the stresses created by the rolls, the quasi-liquid Ti will be under an equilibrium pressure, which can be estimated by the value $P'_{Ti} \approx p$. At this pressure, let us estimate the value of the instability growth rate (1). To do this, we use tabular data characterizing the physical properties of Ti:

– density Ti at melting point – 4110 kg/m^3;

– coefficient of surface tension Ti at the melting point $\sigma = 1.51$ N/m [18];

– kinematic viscosity of molten Ti $\eta_1 = \frac{\mu_1}{\rho_1} =$ =1.01 m^2/s [16].

The effective acceleration resulting from the compression of the samples by the rolls can be estimated by the value $g^* \approx -\frac{1}{\rho_1}\frac{2P_{Ti}}{H}$, where H – the thickness of the mandrel with the tungsten layer, which in the experiment was on the order of $H \approx (3\ldots5)\cdot10^{-5}$ m. Therefore $|g^*| \approx \frac{2}{4110 \text{ kg/m}^3}\frac{10^{-3}\text{Pa}}{4\cdot10^{-5}m} \approx \frac{0.12}{\text{kg/m}^3}\frac{\text{kg/m}^3}{1\ m} \approx 1.2\cdot10^{-2}$m/s^2.

Because the $\rho_1 >> \rho_2, \mu_1 >> \mu_2$, expressions for l_0 and t_0 are simplified and are determined by the quantities: $l_0 = \sqrt{\frac{\sigma}{(g^*\rho_1)}} \approx \sqrt{\frac{1.51}{(0.012\cdot4110)}} \approx 0.17$ m and $t_0 = \sqrt{\frac{l_0}{g^*}} \approx \sqrt{\frac{0.17}{0.012}} \approx 4$ s. For these parameters, the dimensionless kinematic viscosity *Ti* is determined by a quantity on the order of $\mu^* = \frac{\eta_1 t_0}{l_0^2} = \frac{1.01\cdot4}{3\cdot10^{-2}} \approx 1.33\cdot10^2$.

Let us estimate the time of development of the instability of perturbations with the wave number q_{max}, corresponding to the maximum growth rate Λ_{max} for dimensionless kinematic viscosity $\mu^* \approx 133$. Calculations show that $\Lambda_{max} \approx 0.1$; $q_{max} \approx 0.05$. For these parameters, the characteristic time of joining Ti and W is about $t_0/\Lambda_{max} \approx 40$ s. It should be noted that the experimentally selected holding time of the joined metals corresponds in order of magnitude to the above theoretical estimate.

Thus, the physical basis for the connection of Ti and W is the development of the DRTI [14].

CONCLUSIONS

The article considers the process of joining Ti and W by hot rolling in a vacuum (HRV). Based on the analysis of the experimental data obtained and the characteristic parameters of metals, it is proposed to consider the process of their joining within the framework of the problem of the development of the DRTI. This instability describes the motion of the interface between the contacting media as a result of the impact of the compressive force of the rolls. An estimate is obtained for the values of the characteristic time of instability development and the characteristic size of the perturbation of a binary metallic system subject to DRTI. It is shown that the characteristic time of joining Ti and W by the HRV method corresponds in order of magnitude to that observed in experiments.

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ФІЗИЧНА МОДЕЛЬ З'ЄДНАННЯ W И Ti ПРИ ВАКУУМНІЙ ПРОКАТЦІ У ТВЕРДІЙ ФАЗІ

О.Л. Андрєєва, В.І. Ткаченко

Розглянуті альтернативні методи запобігання металевих поверхонь корозійно-ерозійному руйнуванню (КЕР), засновані на гальванізації або на використанні оксидної плівки. Відзначені їхні переваги та недоліки. Для виготовлення стійких до КЕР вольфрамових мішеней, які використовуються у створеній ННЦ ХФТІ підкритичній збірці, запропоновано використовувати метод вакуумної прокатки W і Ti. Захисним покриттям є шар Ti. Для опису процесу з'єднання цих металів запропоновано модельний опис, який ґрунтується на використанні теорії дисипативної нестійкості Релея-Тейлора (ДНРТ). Наведено оцінку значень параметрів бінарної металевої системи, схильної до ДНРТ. Отриманий характерний час з'єднання різнорідних металів відповідає спостережуваному в експериментах.