INVESTIGATION OF SURFACE RESISTANCE OF Al, Be AND Al-Be ALLOY AT LOW TEMPERATURES

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Our work contains experimental and theoretical studies on the surface resistance of aluminium A999, A99 as a function of annealing temperature, frequency of electromagnetic oscillations, cooling temperature and processing technology. Results of investigation of Al-Be alloy surface resistance in a wide range of low temperatures are presented. The technology of the alloy production and treatment for getting the surface resistance lower then that of initial materials (Al, Be) is described. As we have found, this parameter remains to be a constant in a wide range of low temperatures.

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INTRODUCTION

In the process of development and construction of cryogenic accelerators the important problem is reaching a high efficiency of the accelerating structure of accelerator at T>4.2 K without applying the superconductivity and with the use of nonsuperconducting metals. For example, if in a warm variant it is permissible to transform 50% of HF oscillations of energy into the energy of accelerated beam, and if due to using some technological methods the quality factor of the accelerating system can be increased at least by one order of magnitude then the efficiency of energy transform will be not 50% but 90%. And, since this effect will require much simpler efforts than in the case of developing the superconducting accelerator, the final end will be achieved.

In this connection one is interesting in studies on the surface resistance of nonsuperconducting metals at cryogenic temperatures. First of all it is due to that some nonsuperconducting metals have a high electrical conductivity at low temperatures that determines a possibility of practical use of accelerators in a cold variant.

While developing the cryogenic HF-systems it is necessary to analyze the coefficient of gain, η, obtained by the surface resistance of nonsuperconducting metals (equal to the ratio between the surface resistance at room temperature and the surface resistance at low temperatures), depending on cooling temperature, frequence of electromagnetic field, treatment process, material composition.

In this work we performed quite a complex of theoretical and experimental investigations of superconducting metals in a wide temperature range in order to determine which of metals has minimum losses of HF-power and how many times the quality factor of the accelerating structure of accelerator is increased as compared to the accelerating structure operating at room temperature.

MEASUREMENTS

As is known, in the region of classical skin-effect the surface resistance for nonsuperconducting metals is determined from the expression

$$R_k = \left(\frac{\omega\mu}{2\sigma}\right)^{1/2}, \quad (1)$$

where R_k is the surface resistance of nonsuperconducting metal in the region of classical skin-effect, Ohm; ω is the angular frequency of electromagnetic oscillations, rad/s; μ is the magnetic conductivity in vacuum, G/m; σ is the specific conductivity of normal metal at constant current, Cm/m.

In the region of abnormal skin-effect the surface resistance of nonsuperconducting metal is determined from the expression

$$R_a = \left(\frac{1}{b}\right)^{1|3}\left(\frac{l}{\sigma}\right)^{1|2}\left(\frac{\omega\mu}{2}\right)^{2|3}, \quad (2)$$

where b is the coefficient characterizing the reflection of conduction electrons from the conductor surface; l is the length of electron free path.

The coefficient of gain, η, is determined from the expression

$$\eta = \sqrt[6]{\frac{1}{\omega\sigma^3\left(\frac{1}{b}\right)^2\left(\frac{l}{\sigma}\right)^2\mu}}\,. \quad (3)$$

Table 1

$R\cdot10^3$, Ohm	T,	η	F, Hz	δ, μm
4,0 0,26	293 4,2	15,4	0,15	6,74 0,43
17,0 1,8	293 4,2	9,4	3,0	1,54 0,16
24,0 2,7	293 4,2	8,9	5,0	1,14 0,13

In Table 1 the results of calculation for aluminium in the region of classical abnormal skin-effect at frequencies 0.15 GHz, 3.0 GHz, 5.0 Ghz are given, the coefficient of gain η by the surface resistance, and the depth of penetration of high-frequency field into metal δ , for the case of mirror reflection of electrons from the surface are determined. The calculation results show that the coefficient of gain by the surface resistance and the depth of electromagnetic field penetration into metal decrease with increasing frequency.

To confirm the theoretical results on the surface resistance we performed a set of investigations in a wide temperature range on nonsuperconducting metals e.g. A999, A99, A95 aluminium, aluminium-beryllium alloy containing 65 wt% berryllium of commercial purity and 3.5 wt% A95 aluminium and beryllium to determine their dissipative characteristics and to give recommendations on possibility to use nonsuperconducting metals for manufacturing the resonant HF-systems of high-quality operating in the field of low temperatures. To measure the surface resistance at a frequency of 0.15 GHz we used a toroidal resonator, of TEM wave type, and at a frequency of 5 Ghz we used a cylindrical resonator, of H_{111} wave type, with the height equal to its diameter. The latter was manufactured on the turning lathe with subsequent polishing and annealing. By measuring the self- quality factor of such a resonator one can to calculate the surface resistance of resonator material from the expression R=G/Q, where Q is the self-quality factor of the resonator; G is the geometrical factor depending only on the resonator size and on the type of oscillations in it, R is the surface resistance of material.

The high accuracy of measurements of the surface resistance R in a wide range of temperatures, from 293 to 4.2K imposes certain requirements on the design of a resonator the configuration and dimensions of which should be selected so that high-frequency currents of oscillation type under consideration were flowing along the inner side of the resonator without crossing the mechanical joints in the construction. The absence of losses in contacts decreases the measurement error. On cooling the resonator in the frequency band of dominant oscillation mode, the neighboring E_{010}, E_{011} oscillations modes appear that leads to the error in measurements of the resonator quality factor, besides, the shape of a resonance curve of dominant oscillation mode in the measuring resonator takes the distorted view. In this connection, we developed the methods of suppressing the neighboring oscillation modes to the dominant one based on the well-known method of resonator perturbation induced by metallic needles [2]. For measurement of the quality factor of the resonator having the 10^3 order of magnitude we used the resonance method [3]. The quality factor of 10^4 and higher was measured by the method of damping decrement [4].

When measuring the surface resistance of metals the most interest is the self-quality factor of a resonator being defined with taking into account the energy loss at the resonator only. In real facilities any resonator is connected with the outer electric circuits by a feeder, so the energy loss occurs not only in the same resonator, but in the outer circuits, too. To exclude the influence of the outer circuits on the self-quality factor of the resonator the latter was linked with the generator and the indicator using a special probe that was designed as a movable coaxial line with a connection loop situated out of the resonator. The connection loop was shifted inside the round wave conductor connected with the resonator. A high-frequency amplifier was used to provide gaining of the output HF-power coming from the resonator to a level sufficient to use the connection of the resonator with the input- and output HF lead-in via the above-mentioned probe. The non-linear characteristics of the measuring HF section including the amplifier, detecting device and indicator were determined as a function of HF power to find a region where one can measure the temperature dependence of the self-quality factor of a resonator at the same HF power.

The high-frequency investigations of the surface resistance of A999 and A99 aluminium have shown that, depending on the cooling temperature, electromagnetic field frequency, annealing, the lowest surface resistance can be obtained on the A990 aluminium after polishing (P) and annealing (A) at frequencies of f≤0.15MHz (Table 2). At a room temperature the difference in the surface resistance of aluminum of mentioned type is practically absent. The surface resistance of A999 and A99 aluminium at T=4.2 K is 1.2 times higher than that of A95 aluminium. It is due to the alloying composition.

Table 2

Material	$R\cdot 10^3$,Ohm	T, K	η	F, GHz	Treatment
Al A999	4,6 0,39	293 4,2	11,8	0,15	P+A
Al A999	21,0 3,0	293 4,2	7,0	3,0	P+A
Al A999	27,0 4,2	293 4,2	6,4	5,0	P+A
Al A99	21,0 3,6	293 4,2	5,8	3,0	P+A
Al A99	21,0 4,3	293 4,2	4,9	3,0	P

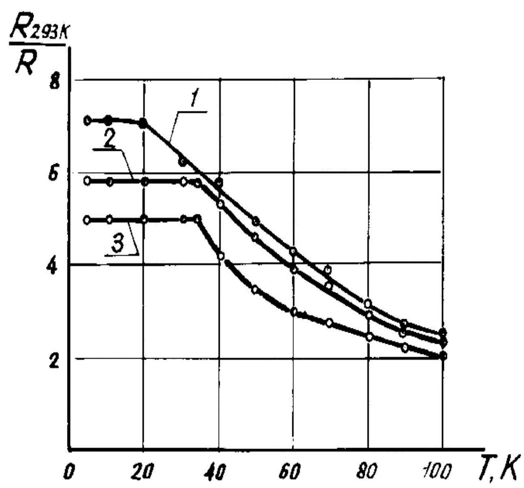

Fig. 1*. The relative surface resistance vs temperature for aluminium of different types.*

Fig. 1 shows the relative change of the surface resistance as a function of the cooling temperature of A999 and A99 aluminium annealed (curve 1,2) and not unannealed (curve 3), the frequency of 3GHz. The investigations performed demonstrated that with the temperature increasing the surface resistance of A99 aluminium decreases much rapidly than that of A99 aluminium. For A99 aluminium the surface resistance reaches a maximum value at T=34K (curve 2), and for A999 aluminium the surface resistance changes up to the temperature of 4.2K (curve 1). The coefficient of gain η for annealed A99 aluminium is by 18% higher than that of unannealed aluminium.

In Table 3 the results of measurements of the surface resistance at a frequency of 5.0 GHz for aluminium-beryllium alloy, A95 aluminium after turning work (TW), polishing (P) and annealing (A) are presented.

As follows from the experimental results in the range of low temperatures the AL-Be alloy has a surface resistance less than that of starting components (Al, Be) and stays constant in the wide range of temperatures from 50 to 4.2 K (Fig. 2, curve 1).

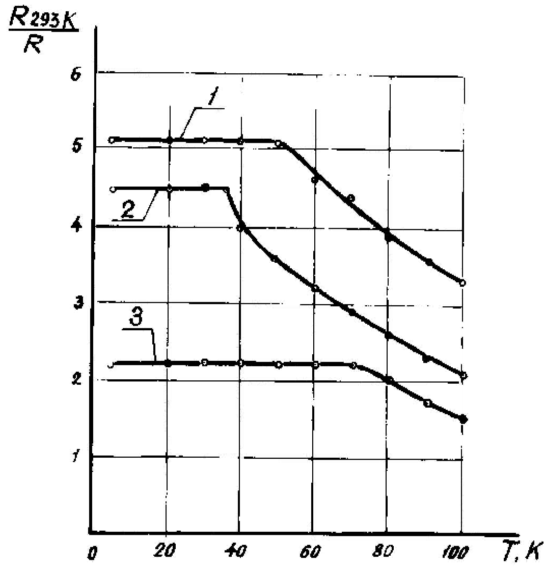

Fig. 2. *The relative surface resistance vs temperature for Al-Be and Al, Be (curves 1-3, respectively).*

Table 3

Material	$R\cdot10^3$, Ohm	T, K	η_1	η_2	Treat-ment
Al-Be	44,0 11,0 8,6	293 77,3 4,2	4,4	5,1	TW+P +A
Be	110,0 52,0 50,0	293 77,3 4,2	2,1	2,2	TW+P +A
Al A95	32,0 13,0 7,1	293 77,3 4,2	2,5	4,5	TW+P +A

For aluminium the coefficient of gain reaches its maximum value at a temperature of T=35K (curve 3) and for beryllium T=70K (curve 3).

CONCLUSION

For the Al-Be alloy the coefficient of linear expansion is invariable in a wide range of low temperatures and therefore this alloy can be successfully applied as a structural material for manufacturing the components of accelerating structures of the accelerator operating in a wide range of temperatures from 50 to 4.2K So, to attain the optimum parameters of HF-systems in the range of cryogenic temperatures, i.e. to increase appreciably the quality factor for decreasing the losses of high-frequency energy, as well as to improve the stability and invariability of properties at a temperature from 4.2 to 50 K the AL-Be alloy is preferred to be applied. This will allow one to reduce the consumption of expensive cryogenic liquids, to decrease the service expenses. Furthermore, the Al-Be alloy has a low density and high elasticity and possesses a high technological productivity at the process of manufacturing the products of a given form: pressing by rolling, machining [5].

Using the known interpolation formula ([6])

$$R_n = R_a(1 + 1{,}157\alpha^{-0{,}2757}) \quad (4)$$

where α is the characteristic parameter in the anomalous skin-effect theory (α>1,2), we have found also the intermediate region between the classic and anomalous skin affect for Al-Be alloy.

The calculation results have shown that the intermediate region between the classical and abnormal skin-effects for the Al-Be alloy at a frequency of 5.0 GHz appears at a temperature T~150 K, the coefficient of gain η equals to 10 at a frequency of $86\cdot10^6$ GHz. So, to increase the quality factor of the accelerating structure of the accelerator by a factor of 10 and more it is necessary to work at frequencies f≤86 MHz.

REFERENCES

1. F.F. Mende, A.I. Spitsyn. *Surface impedance of superconductors.* Kyiv, Naukova Dumka.1985, p. 20-36 (in Ukrainian).
2. E.L. Hinston. *Measurements on the centimeter waves.* Translation from English, edited by G.L.Remez, Inostrannaya Literatura. 1960, p. 545-549 (in Russian).
3. V.A. Dvinskikh, Yu.P. Naumenko. Measurement of the quality factor of microwave resonators // *Prib. Tekhn. Ehksp.* 1969, N 1, p. 5-12, (in Russian).
4. E.I. Kulikov. Measurement of the quality factor of cavity resonators with low damping// *Izmerit. Tekhnika*. 1959, N6, p. 55-57 (in Russsian).
5. I.I. Papirov. *Beryllium-structural material.* M.: Mashinostroenie. 1971, p. 142-143 (in Russian).
6. R.G. Chambers. The anomalous skin effect // *Pros. Roy. Soc*. 1952, v. A215, p. 1123-1125.