Design of a compact microwave-absorbing load based on sintered material FeSiAl

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Abstract. The dummy load in the terminal of traveling wave tubes is an important component of compact high-power electron linear accelerators. To develop high-power loads and miniaturize the accelerators, a microwave-absorbing material FeSiAl coated by a special sintering process is employed to enhance the efficiency of attenuation. Based on the method of multistate and multithickness, the complex permittivity and permeability of the material FeSiAl was obtained. And the design of a compact S-band dummy load was done by means of an engineering design and analysis system. With a very short length of less than 250mm, this dummy load is able to dissipate 10kW residual power to ensure the security of the accelerator. It can provide an important reference for the design of the high-power compact dummy load.

1. Introduction
Since the conception of RF linear accelerator (LINAC) has been advanced by G. Ising in 1924, and tested by R. Wideröe in 1928, many LINACs have been built in the world for science researches and applications in different field, such as SNS, LCLS, ERL, nuclear medicine, industrial, agriculture, food safety, material science, and so on. All of these facilities are composed of many components, such as accelerating structure, waveguide, RF dummy load, RF power attenuator and high-order-mode absorber in accelerator cavity. Dummy load is a high power device intended to absorb the residual power to ensure the accelerator working properly. According to the difference of the absorbing media, dummy load can be divided into water load and dry load two types. The water load is limited by the lower mechanical strength despite the characteristics of high power capacity [1]. In comparison, the dry load has been widely used in many LINACs benefitted from the security and reliability [2, 3]. Among it, coaxial loads are generally known as terminations and typically they are able to handle relatively small power due to the demand of the resonant frequency [4]. As another form, waveguide dry loads have been widely used benefitted from the applicability [5, 6]. But there are also several disadvantages, such as the huge size, restrict the further application.

Given the trend of the miniaturization and mobility of LINAC to promote the applications, the compact of the dummy load is getting more and more attentions. Aimed to absorbing 10kW residual power with a length of less than 250mm, a waveguide dry load coated with an efficient absorbing medium FeSiAl is designed to satisfy the demand of a compact electron LINAC used for a THz-source. Systematical simulation and analysis are required for the optimization of the dummy load.
2. Measurement of the electromagnetic parameters
Whether it is the waveguide load or the coaxial load, the basic principle is converting the microwave energy into heat by the absorbing material attached to wall of the cavity. The properties of the microwave absorbing material relate directly to the performance of the dry load. A kind of FeSiAl alloy coated on a copper base produces several excellent properties, such as good thermal conductivity, a low outgassing rate and high microwave absorption rate. The coating was formed by a special high sintering process in a vacuum furnace by our collaborators, resulting in a multilayer material with a thickness of less than 0.5 mm. They have done a lot of research on the preparation techincs of the material and found that only in this way can the coating be more efficient in absorbing the microwave power than others. And the coating by this process has been successfully used in the klystron [7]. It has also been found that being different from other general absorbing materials, the coating layer benefits from both its chemical components and its microstructure. In order to the miniaturization, FeSiAl is chosen as the substitute for the traditional absorbing material.

In designing a dummy load for the electron LINAC, Thorough knowledge about microwave absorbing materials is very important. And the simulation of the load will be very difficult if the permittivity and permeability of the material are inaccurate. Considering the particularity of the multilayer coating and the applicability of the relative methods, the method of multistate and multithickness in which the performance of the sample is the same as the factual is adopted to measure the permittivity and permeability of the FeSiAl coating. A simple structure for the measurement was designed as shown in Figure 1. This is basically a wedge-shaped section of standard rectangular waveguide (a × b) that has been terminated with an inclined short-circuit plate coated with FeSiAl. The relationship between the attenuation coefficient and the electromagnetic parameters of the material could be obtained by adjusting the slope of the short circuit plate (expressed by the length of the plate in the horizontal direction Lt as the length of the narrow side of the standard waveguide b is a constant) and the thickness of the coating (mt).

Based on the electromagnetism theory, the complex permittivity and permeability of FeSiAl at 2.856 GHz, the working frequency of the S-band LINAC, were calculated to be \(\varepsilon = 114.22 - 15.81i\), \(\mu = 1.09 - 1.98i\). And the verification test of a welded sample with FeSiAl coated on its inner surface shows that the error of the attenuation coefficient between the measurement and calculation is less than 2%. With this, the measured permittivity and permeability of the FeSiAl coating could be used for the further simulation.

3. Theoretical design of the dummy load
In order to prevent the residual power from interfering with the normal operation of the accelerator, the attenuation of the load must be above 32dB. The distribution of the FeSiAl coating in the waveguide cavity should be optimal designed to satisfy the actual working requirement. For the simplest waveguide load as the measuring structure with only one internal surface coated, the influence of the thickness of the coating and the length of the slope in the horizontal direction are analyzed as shown in Table 1 in the way of analysis of variance (ANOVA).
It can be seen that both of the two structure parameters have a significant impact on the attenuation as the two values of F-statistics are much larger than the critical value. However, it is difficult to distinguish the primary and secondary between the two. A more decisive parameter should be concluded to provide reference for the design. Based on the previous research, the FeSiAl coating is known as volume absorption in the collinear load [8]. The relationship between the volume of the coating and the attenuation in the waveguide load with only one internal surface coated are then summarized as shown in Figure 2. The attenuation of the load increases approximately in a line with the increase of the volume of the coating, accompanied by minor fluctuations. Therefore, the structure with all internal surfaces coated is adopted to shorten the length of the dummy load.

Table 1. ANOVA of the thickness and length.

| Difference       | SS   | df | MS  | F      | P-value | F-crit |
|------------------|------|----|-----|--------|---------|--------|
| Thickness (mt)   | 19115.7 | 48 | 398.2 | 20.11  | 4.48E-53 | 1.42   |
| Length (Lt)      | 11113.6 | 4  | 2778.3 | 140.31 | 7.46E-56 | 2.42   |
| Error            | 3802.1 | 192| 19.8 |        |         |        |
| Total            | 34031.34 | 244|      |        |         |        |

Figure 2. Coating volume effects on the attenuation.

To avoid the overconcentration of the heat and the shedding of the coating, the FeSiAl material is coated on the internal four surfaces of the rectangular waveguide with varying section with a thickness of 0.3mm. A short standard rectangular waveguide is reserved without coated not only for the impedance matching but also for the machining process, which can be regarded as the entrance of the attenuation section. Under the conditions of limited total length and fixed size of the entrance, the cross-sectional deformation of the attenuation section determined by the length of the width side and the narrow side at its extremity, a-g and b-g, relates to the performance of the load. The simulation results of a-g and b-g adjustment for a waveguide load with a total length of 200mm are recorded in Figure 3, which shows that the attenuation increase with decrease of the width of the terminal while there is an extreme point for the length. This is because the volume of the coating decreases with the decrease of the width, and because the electromagnetic field intensity increases with the decrease of the cross-sectional area of the terminal.
After considering the influence factors comprehensively, the attenuation goes for a maximum while the wide sides of the waveguide load at the terminal are touching and there is a special spacing between the narrow sides. In our solution, the input reflection coefficient at the working frequency is 32.9 dB and bandwidth is 8% at 500MHz while the total length of the waveguide load is only 210mm with a 32mm spacing between the narrow sides.

![Figure 3](image-url)  
*Figure 3. The attenuation vs. the length and the width.*

4. Temperature filed analysis of the load

In order to guarantee the dummy load working properly, a jacket-type cooling structure with a single-inlet helix water channel is also designed to carry away the 10kW heat. An electromagnetism-fluid-thermal coupled analysis in the ANSYS is adopted to determine the cooling parameters [9, 10]. After repeated optimization simulation, the transverse dimensions of the rectangular water flow channel are chosen as 30mm×10mm. The temperature distribution and cold/hot spots of the dummy load are demonstrated in the Figure 4. The maximum temperature of the coating part is only 39.1°C with a flow rate of 0.75 kilograms per second while the pressure drop is 0.29Mpa, smaller than the allowable design value 0.3Mpa.

![Figure 4](image-url)  
*Figure 4. Temperature distribution of the absorbing section.*
By comparing the structure before and after, it could be also found that the maximum thermal deformation of the dummy load is only 27μm, which is not enough to cause the attenuation performance degradation. From these results, a supporting water cooling system is obtained, which can make the high power dummy load work well.

5. Summary and Conclusions
A compact high power RF dummy load was designed with an efficient microwave absorbing material FeSiAl. This dummy load was designed for 10kW average input RF power with very low input reflection coefficient S11≤-32.9dB and the total length is only 210mm. And a cooling system was devised to ensure the load working properly.

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