Resistance Welded Joint of Ti6Al4V Alloy-PEI/GF Composite Reinforced By Candle Soot Coating

Daosheng Wang, Xu Cui*, Jiapeng Dong, Yingfan Deng and Lin Tian
Shenyang Aerospace University, Shenyang Aerospace University, 110136, Shenyang, China

*Corresponding author e-mail: shuowang@sau.edu.cn

Abstract. PEI/GF lamination and Ti6Al4V alloy are often related to the poor wettability of PEI to Ti6Al4V alloy at the interface layer. To overcome these problems, an in situ synthetic candle soot reinforcing coating on Ti6Al4V alloy was added into the place of the bonding area. The mechanical properties of composite joints were evaluated by single lap shear strength (LSS) tensile test. The mechanism of strengthening Ti6Al4V-PEI/GF joint by candle ash was compared.

Keywords: Candle Soot, Ti6Al4V, Polyetherimide, Resistance-Welding, Wettability

1 Introduction
There are two great materials of high specific stiffness. They are Ti6Al4V alloy and advanced composite [1] include mechanical fastening and bonding. However, mechanical fastening also has many inevitable disadvantages, such as high-stress concentration and significant weight gain, especially when metal bolts [2] are used. Adhesion is time-consuming because it requires a long curing reaction and surface treatment [3]. This scheme can perfectly construct the efficient connection between Ti6Al4V alloy and composite material and has received extensive attention in welding technology, especially in resistance welding technology. Resistance welding has the advantages of high welding efficiency, less filling materials, simple equipment and machinery, wide welding range, etc., and can be used large aviation structural parts through [4]. It is regarded as the most promising connectivity technology in the 21st century in terms of aerospace applications [5-6].

Ti6Al4V alloy members are connected to multiple parts by simple RW technology, which has a great prospect in the making process of many spacecrafts. This surfaces of metals [7] are modified by etching, sandblasting, plasma spraying, laser deformation, anodic oxidation, and silane super primers. However, carrying out the Ti6Al4V surface treatment requires expensive and complex scientific equipment and incalculable damage to the environment.

Carbon nanotube, graphene [8], carbon soot [9], and other carbon micro-nano materials have a great high length ratio, good superhydrophobicity, and superoleophobic properties. Especially, candle soot, as a kind of hydrophobic and superhydrophobic material, has been widely used in the surface modification of template or auxiliary materials to adjust the wettability of the interface surface. Chen. et al designed a copper mesh modified by carbon nanoparticles during the candle combustion to
effectively separate oil and water. Candle soot coating was deposited on the surface of ferroelectric ceramics by Vaish et al. [10] to fabricate a tunable surface. For metal-polymer bonding, flame growing candle soot coating on metal plate surface treatment is beneficial to improve the wettability of polymer to metal, thus improving the overall strength of multi-dimensional welded joints.

The purpose of this study was to investigate the effect of candle soot coating on Ti6AL4V alloy surface treatment, and then to investigate the enhancement of interface strength between the Ti6AL4V and PEI/GF lamination. This remarkable bad ways of the joint were systematically analyzed and studied by visual method and scanning electron microscopy. Besides, a detailed mechanical analysis is made on the binding mechanism of surface treatment.

2 Experimental

2.1 Material

Ti6AL4V alloy plate is provided by Sichuan Hada Xiweta New Material Technology Co., LTD. Candles were purchased from Hubei Tianguo, Hubei, according to receiving standard.

2.2 Synthesis of Candle Soot on the Place of Ti6AL4V Plate

The preparation principle of candle smoke on the surface of Ti6AL4V alloy is shown in Fig. 1a. Firstly, Ti6AL4V alloy was cleaned with acetone for 100 min to completely remove the dirt and organic pollution on the metal surface. Then, a candle is lit and burned for a period of time so that the candle flame remains continuous and steady. The Ti6AL4V plate is then placed directly on top of the 2 cm flame. During the burning process, a large amount of candle smoke gradually deposits on the surface of the plate. The total deposition time was 2 min (Fig. 1b).

2.3 Welding Process

The SS mesh was put into the welded position between PEI/GF lamination and Ti6AL4V plate, and a 0.2 MPa was applied to the welding. The power is 40 V, the current is 20 A, and the welding time (t_w) is 200 s. In the welding process, the two edge parts of the welding are actively air-cooled. Two temperature sensor were added to the weld with PEI mask to test the welding, and then the data curve of the bonding area was collected synchronously (Fig. 1c).

2.4 Characterization

The detailed microstructure of the candle soot and welding parts was observed by SEM and TEM was used to characterize the microstructure parameters of soot from candles.

LSS of the connector was tested by a universal tester (Instron 8801, USA) with a crosshead speed of 10 mm/min, according to the standard of D1002 of The American Society for Testing Materials. More than 5 samples, and the results showed mean LSS calculation formula is as follows:

\[
\tau = \frac{F_{\text{max}}}{L \times b} \left[ \frac{N}{\text{mm}^2} \right]
\]  

(1)

Where \(F_{\text{max}}\) is the maximum tensile force, N; \(\tau\) is a single lap shear strength, N/mm^2; \(b\) is the lap width, mm; \(L\) is the lap length, mm.
Fig. 1 (a) The schematic diagram of preparing the candle soot on Ti6Al4V alloy; (b) candle soot coating on the surface of Ti6Al4V alloy; (c) the schematic diagram of welded joint composition.

3 System Results and Discussions

3.1 Effects of Candle Soot on the Wettability of the PEI Resin on Ti6Al4V Alloy

Due to the coating of oxidized film, the surface of the Ti6Al4V is relatively smooth relative to the base material (Fig. 2a, 2b). In order to improve the mechanical properties of the PEI/GF laminating joint of the Ti6Al4V plate, the surface of the Ti6Al4V alloy plate was modified by wax fume. As shown in Fig. 2c, the candle soot coating on the candle grew in situ from the burning of the candle flame. Candle soot is evenly of the Ti6Al4V plate (Fig. 2d), which is composed of many nanoscale particles. The chaotic accumulation of nanoparticles results in the formation of a fractured porous network structure (Fig. 2e).

![Fig. 2](image-url)

Fig. 2 (a, b) SEM images of original Ti6Al4V alloy; (c-e) SEM images of candle soot-modified Ti6Al4V alloy

3.2 Interface Structure and Mechanical Properties of Ti6Al4V-PEI/GF Joint

Fig. 3 shows the shear strength of the Ti6Al4V-PEI/GF welded joints. This LSS value of the joint with wax ash is higher than that of the joint without candle soot. The average LSS of the joint welded with unwaxed soot was 7.62 mpa, and that of the joint welded with candle soot was 18.36 mpa. The optimum LSS of the joint with candle ash enhanced coating was 140.9% higher than that of the joint without candle soot. It indicates that the candle soot coating had a more effective strengthening effect compared to Ti6Al4V alloy for improving the mechanical properties of the bonding joint.

![Fig. 3](image-url)

Fig. 3 The lap tensile shear strength of the Ti6Al4V-PEI/GF joint

3.3 Strengthening Mechanism of Candle Soot on Ti6Al4V-PEI/GF Joints

Seeing these fracture pictures of the welded joints, we know that the failure mode was interlayer failure (Fig. 4a and 4d). And the entire implant was tightly attached to the PEI/GF lamination welded area. The place of the failed Ti6Al4V alloy was very smooth (Fig. 4b). And there is no effective connection between PEI and Ti6Al4V alloy (Fig. 4c), so the interface strength was low. Conversely, there are PEI stuck on the place of the candle soot-incorporated Ti6Al4V alloy in undulating form (Fig. 4e). A large amount of candle soot has also adhered to the implant interface (Fig. 4f).
Fig. 4 (a-c) Failure interface of pure Ti6Al4V-PEI/GF joint; (d-f) failure interface of candle soot-modified Ti6Al4V-PEI/GF joint

To further study the influence of candle soot on welded joints, the SM of welded joints was studied. First, PEI resin was heated and melted during the heating process of the SS network. The flowing resin penetrated the pores of the SS network and pits on the surface of the rough welds under the capillary action of the high porosity candle soot (Fig. 5b). Therefore, a dense soldering interface can be fabricated at the welded joint (Fig. 5c). Conversely, the exposed surface of alloy could not provide a high-strength interface for resin/Ti6Al4V alloy (Fig. 5a). Secondly, candle soot on the surface of the Ti6Al4V alloy can provide an effective attachment site for the PEI resin between PEI resin and candle soot coating in the process of interface failure. The smooth surface of Ti6Al4V alloy could not act as PEI resin and alloy to the strength.

Fig. 5 Schematic diagrams of strengthening mechanism

4 Conclusion
The largest LSS of the joint welded was 18.36 MPa. The best LSS with candle soot reinforced coating is add to 140.9 % with the joint with no candle soot. Fracture modes was determined for samples welded without candle soot and with candle soot, which behaved as an interlayer failure. The mechanism about candle soot enhanced welding interface was proposed.

Acknowledgments
The financial support from Liaoning Natural Fund Project in 2019 (No. 2019-ZD-0246), National (outside) training project of Liaoning higher education institutions (No. 2018-LNGXGJWPY-YB008) are gratefully acknowledged.

References
[1] Zhang Dawei, Zhang Qi, Fan Xiaoguang, Zhao Shengdun: Review on joining process of carbon fiber-reinforced polymer and metal: applications and outlook. Rare Metal Materials and Engineering 48(1), 44-54 (2019).(in Chinese).
[2] Li Dezhi, Chrysanthou Andreas, Patel Imran Williams Geraint: Self-piercing riveting-a review. International Journal of Advanced Manufacturing Technology (2017).(in UK).
[3] S. Budhea, M.D. Banea, S. de Barrosa, L.F.M. da Silva: An updated review of adhesively bonded joints in composite materials. International Journal of Adhesion and Adhesives 72, 30-42 (2017).(in Portugal).
[4] Xiong Xuhai, Zhao Pu, Ren Rong, Zhang Zhongbao, Cui Xu, Ji Shude: Design of reinforced interfacial structure in hybrid resistance-welded joints of PEI/GF composite and Ti6Al4V alloy by pre-etching surface treatment combined with in-situ growth of CNTs. Engineering
Research Express 1, 015023 (2019).(in Chinese).

[5] Xiong Xuhai, Zhao Pu, Ren Rong, Zhang Zhongbao, Cui Xu, Ji Shude: Effect of chemical etching of resistance wire surface on the strength and failure mechanism of the resistance-welded joint of polyetherimide composites. Journal of Applied Polymer Science 136(34),47879 (2019).(in Chinese).

[6] Nagatsuka Kimiaki, Xiao Bolyu, Wu Lihui: Dissimilar materials joining of metal/carbon fibre reinforced plastic by resistance spot welding. Welding International 32(7), 505-512 (2018).(in Japanese).

[7] Krmer E T M, Gouve W J B, Koussios S, Warnetb L.L., Akkermanl R.: Real-time observation of waviness formation during C/PEEK consolidation. Composites Part A : Applied ence and Manufacturing, 105872 (2020).(in Netherlands).

[8] Zhang Lin, Li Hongqiang, Lai Xuejun, Su Xiaojing, Liang Tao, Zeng Xingrong: Thiolated graphene-based superhydrophobic sponges for oil-water separation. Chemical Engineering Journal 316, 736-743 (2017).(in Chinese).

[9] Nagatsuka Kimiaki, Xiao Bolyu, Wu, Lihui: Dissimilar materials joining of metal/carbon fibre reinforced plastic by resistance spot welding. Welding International 32(7), 505-512 (2018).(in Japanese).

[10] Priyanka Singh, Sampat Singh Chauhan, Gurmeet Singh: Anticorrosion and electromagnetic interference shielding behavior of candle soot-based epoxy coating. Journal of Applied Polymer Science, 2020, 137(19) (2020).(in Italy).