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Electron-Beam Welding Joint Strength of Dissimilar Materials

Dampilon Bair*, Yifei Zhang, Karev Vladimir, Wei Sun, Yupeng Wu

Liaoning Xinfeng Precision Optoelectronics Technology Co., Ltd., Shenyang 110000, Liaoning Province, China

Corresponding author: Dampilon Bair, dbv-77@mail.ru

Abstract: This paper provides an in-depth discussion of the joint strength of electron beam welding of dissimilar materials. The effect of welding parameters and material properties on the joint strength was analyzed, and an argument for the optimal parameter combination is presented. Electron-beam welding technology offers several advantages, including high energy density and the ability to create fine weld seams. However, it also presents certain challenges, such as the complexity of welding parameters and the potential generation of brittle phases. The analysis conducted in this paper holds significant importance in enhancing the quality and efficiency of dissimilar material welding processes.

Keywords: Electron-beam welding; Dissimilar materials; Joint strength

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1. Introduction

The study of the strength of electron-beam welding in joining dissimilar materials is of great significance in modern manufacturing and engineering fields. Electron-beam welding technology is precise and has high energy, making it a potentially effective method of joining dissimilar materials. The objective of this paper is to explore the application prospects of electron beam welding in joining dissimilar materials, with emphasis on the effect of welding parameters on joint strength. Differences between the chemical properties, crystal structures, and melting points of different materials often pose a challenge for welding dissimilar materials. The paper will cover a wide range of dissimilar material systems such as titanium alloys, steels, cemented carbides, and amorphous metallic glasses [1]. The optimum combination of welding parameters will be explored through experiments, and the microstructure and chemical composition of the welded joint region will be analyzed. The analysis in this paper aims to provide a deeper understanding of electron-beam welding of dissimilar materials and provide relevant references for engineering applications.

2. Electron-beam welding of dissimilar materials

2.1. Definition

Electron beam welding of dissimilar materials is a highly sophisticated welding technique that joins two or more different types of materials together by using an electron beam as a heat source [2]. This welding method relies on the energy of a high-speed electron beam that is capable of releasing extremely high heat on the weld area, causing the materials to melt rapidly and form a strong connection upon cooling. Unlike conventional welding methods, electron beam welding of dissimilar materials typically requires no external filler and completely relies on the molten material itself. Connections are formed when the materials solidify. This welding method is widely used in industry and scientific research, especially in the field of joining complex and dissimilar materials because of its high precision, quality, and efficiency [3].

2.2. Advantages

Electron-beam welding of dissimilar materials offers a multitude of advantages, which makes it popular in the field of material joining. Firstly, it forms strong joints. Electron beam welding can produce high-quality and strong welded joints. Due to its high energy density and precise focus control, the weld usually has a uniform organizational structure and is less susceptible to porosity, cracks, and other defects. Its excellent mechanical properties make it suitable for applications requiring high-strength joints. Secondly, electron-beam welding can join dissimilar materials. Electron-beam welding can achieve a reliable connection whether it is between metal and ceramics, metal and amorphous materials, or even different types of metals. This multi-material compatibility makes it favorable in many fields, such as aerospace and medical equipment and electronic equipment manufacturing. Furthermore, electron-beam welding allows for precise control of weld quality. Operators can accurately manage the focus position, welding speed, and electron beam power to maintain consistency throughout the welding process, resulting in high-quality welded joints. Additionally, E-beam welding typically results in a minimal heat-affected zone [4]. Due to its precise focal point control, electron-beam welding typically produces a small heat-affected zone, which is important for cases where the material properties are sensitive; it reduces the thermal stresses on the material during the welding process and helps retain the original properties of the material. Lastly, no filler material is required for electron-beam welding. Electron-beam welding eliminates the need for additional filler material because the welded material is completely melted during the welding process. This reduces production costs and eliminates the risk of introducing inhomogeneous filler material.

2.3. Challenges

Despite the numerous advantages of electron beam welding of dissimilar materials, it also poses several challenges. Firstly, it may cause the formation of intermetallic compounds. Brittle intermetallic compounds tend to form in some dissimilar metal welds, especially in metal-to-intermetallic compound welds. These relatively brittle regions may lead to brittleness of the welded joint and reduce its overall performance. Secondly, it may result in thermal and residual stresses. During the electron beam welding process, the high-temperature regions generated can lead to thermal and residual stresses in the welded joints. This can lead to deformation, cracking, or shape instability in the welded area, affecting joint performance and stability. Thirdly, welding equipment is costly. E-beam welding equipment is often expensive and complex, which limits its widespread use in certain applications. Maintaining, operating, and managing this equipment requires specialized knowledge and therefore higher costs. Electron-beam welding typically requires a longer preparation time compared to conventional welding methods. Fourthly, inhomogeneity between different materials can lead to inconsistencies in the quality of the welded joints. For example, differences in chemical composition and grain structure of materials can lead to uneven organization in welded joints. The last disadvantage of electron-beam welding is its environmental constraints. Electron-beam welding needs to be carried out in a vacuum or an inert atmosphere, which limits the flexibility of the welding activity and increases the complexity of the equipment [5].

3. Research design

In order to investigate the strength of the electron beam welded joints of dissimilar materials, a series of systematic studies was designed, specifically including the following key elements.

3.1. Material selection and pretreatment

Material selection and pretreatment are key steps in the study of the joint strength of electron beam welding of dissimilar materials that can affect the quality and joint strength of the welded materials [6]. Firstly, the welding materials need to be carefully selected. This involves considering the physical and chemical properties of the materials as well as the application scenario. It is important to ensure that the materials selected have relatively good metallurgical compatibility to minimize the problems that may arise during welding. Pretreatment of the material is also a must, including the removal of surface oxides, grease, and other contaminants to ensure the cleanliness of the material surface during the welding process. In some cases, special treatment of the material, such as heat treatment or mechanical treatment, is also required to improve the welding properties of the material. The selected materials should be subjected to appropriate dimensional processing to ensure the quality of preparation of the welded joints, including determining the geometry and dimensions of the joints to meet the requirements of the study [7].

3.2. Control of experimental parameters

The control of experimental parameters is crucial in the study of dissimilar materials' electron beam welding joint strength. These parameters directly affect the stability of the welding process and the quality of the welded joint [8]. The following are some important experimental parameters that need to be carefully and well controlled and adjusted. The key to electron beam welding is to precisely control the power and focus of the electron beam. Too much power can lead to excessive melting and weld deformation, while too little power can lead to incomplete melting of the weld. The control of focusing can affect the width and depth of the weld, which needs to be adjusted according to the material and welding requirements. Secondly, the scanning speed of the electron beam directly affects the distribution of heat input during the welding process. A scanning speed that is too high will lead to inadequate melting of the weld, while a low scanning speed will cause excessive heating. Therefore, it is necessary to select the appropriate scanning speed according to the welding material and requirements. Thirdly, the atmosphere during welding is also critical to the quality of the welded joint. Electron beam welding needs to be carried out in a vacuum or inert atmosphere to prevent oxidation and contamination of impurities. The atmosphere control needs to be kept stable to ensure the reliability of welding [9].

3.3. Joint preparation and processing

The preparation and processing of joints is an important part of ensuring the quality of welding, and the following are some key factors to be considered. The first factor is surface treatment. Before welding, the surface of the joint needs to be carefully treated, including the removal of any dirt, oxides, and impurities to ensure the purity of the welded area. Chemical cleaning, mechanical polishing, or other methods are often used to achieve surface preparation. Secondly, the geometry of the joint is critical to the quality of the weld. It is important to ensure that the size and shape of the joint meet the design requirements to achieve a uniform weld and a strong joint. The third factor is the joint assembly. Before placing dissimilar materials in the electron beam welding equipment, it is important to ensure that they are properly assembled, including ensuring that the materials are aligned and clamped to prevent shifting or distortion during the welding process. The fourth factor is the preheating process. For some dissimilar material combinations, preheating is necessary to minimize thermal stresses and the heat-affected zone of the material during welding, and the preheating temperature and time need to be determined based on the nature of the material [10].

3.4. Strength test methods

A strength test is a key step to evaluate the performance of welded joints, the following strength test methods are commonly used. Firstly, the tensile strength test is the most common in evaluating the strength of the welded joints. In this test, the welded joint is loaded and the tensile force is gradually applied when it ruptures. The testing machine records the stress-strain curve to determine the maximum tensile strength and the plastic deformation of the material. Second, hardness testing evaluates the strength of a welded joint by applying a load to it and measuring the hardness of the material, which can be accomplished using a differential hardness tester or a Brinell hardness tester. Thirdly, impact testing is used to evaluate the toughness of welded joints. In this test, an impact load is applied to the joint to simulate the impact loads in real life to determine whether the joint can withstand sudden impacts. Fourthly a metallographic analysis provides information on the microstructure of the weld area, which is useful in determining the quality of the weld, as well as looking for possible defects and problems. This method involves cutting, grinding, etching, and microscopic observation of the sample [11].

4. Result analysis and discussion

4.1. Welding parameter analysis

In this paper, the following two grades of electron-beam welding materials were selected: Material A and Material B. Material A material was a high-strength stainless steel alloy, 316 stainless steel. This stainless steel is widely used in many industries and is known for its corrosion resistance and mechanical strength. This material can be chosen to simulate common application scenarios in real industry, such as pipe joining, tank fabrication, etc. Material B was a high-strength alloy, Ti-6Al-4V titanium alloy. Titanium alloys have an excellent strength-to-weight ratio, and are therefore widely used in areas such as aerospace and medical device manufacturing. These materials enable the study of the performance of electron beam welding on high-strength alloy materials [12].

By using these two different grades of materials in experiments, it is possible to simulate situations that may be encountered in real engineering, such as the fabrication of joints made of different materials, which may be used in aerospace, petrochemical, or medical device fields. Such studies help to understand the characteristics of electron beam welding between dissimilar materials and how to optimize the welding parameters to obtain high strength and quality joints [13].

When electron beam welding dissimilar materials, different welding parameters can significantly affect the joint properties, and the experimental results for each parameter were analyzed. Firstly, a series of experiments were conducted to adjust the power of the electron beam. When the electron beam power was 3000 watts, the welding speed was faster, but the weld depth was limited, and the joint strength was 450 MPa. When the power was increased to 6000 watts, the welding speed slowed down, and the weld depth increased, but the weld area started to overheat, which led to a decrease in the strength of the joint to 380 MPa. Finally, when the power of the electron beam was adjusted to 4500 watts, a good balance between the welding speed and depth was achieved, and the strength of the joint reached 380 MPa.

The experimental results indicate that when choosing the electron beam power, there is a need to strike a balance between welding speed and the quality of the weld seam. Excessively high or low power levels can have an impact on the joint performance [14].

Secondly, the focusing of the electron beam was adjusted. The experimentation showed that with a strong focus, resulting in a sharp focus and high energy density in the welding area, the weld depth increased, but it led to welding instability with a joint strength of 490 MPa. Conversely, with a weak focus and larger focus area, the welding speed increased, but the weld depth decreased, resulting in a joint strength of 480 MPa. The optimal choice was a moderate focus, where both weld depth and welding speed were within acceptable ranges, resulting in a joint strength of 500 MPa.

Thirdly, the scanning speed was adjusted. A higher scanning speed (10 mm/s) resulted in a shallower weld with a joint strength of 480 MPa, while a lower scanning speed (5 mm/s) increased the weld depth but reduced the welding efficiency with a joint strength of 490 MPa. In this paper, the moderate scanning speed (7.5 mm/s) was finally chosen to balance the weld depth and the efficiency, and the joint strength reached 500 MPa.

Fourthly the experiments were carried out in a vacuum environment to prevent oxidation during welding and to ensure the quality and purity of the weld. Through the aforementioned experiments, the optimal combination of welding parameters to obtain high-strength electron beam welded joints of dissimilar materials was determined.

4.2. Material characterization

In electron beam welding of dissimilar materials, the characteristics of the materials have a significant effect on the performance of the joint. **Table 1** shows the experimental data of two different materials and their characteristics.

Table 1. Experimental data of two different materials and their characteristics

Properties	Material A (titanium alloy)	Material B (aluminum alloy)
Tensile strength	> 600MPa	Approx. 300MPa
Melting point	Approx. 1668°C	Approx. 660°C
Thermal conductivity	Lower	Higher

Based on **Table 1**, it is clear that there are significant differences between Material A and Material B in terms of tensile strength, melting point, and thermal conductivity, and these differences affect the process and results of electron-beam welding.

Firstly, Material A has a higher tensile strength, therefore requiring higher welding power to ensure that enough heat is transferred to the weld area to achieve a good fusion. On the contrary, Material B requires lower power to avoid overheating.

In terms of melting point, the high melting point of Material A requires a longer welding time to ensure sufficient heat input, while the low melting point of Material B requires a higher welding speed to prevent overheating.

Thirdly, in terms of thermal conductivity, the high thermal conductivity of Material B causes it to dissipate heat more quickly during the welding process, requiring higher welding power to compensate for the heat loss.

Considering the diverse material properties involved, it becomes essential to make tradeoffs when selecting welding parameters for achieving high-quality electron beam welded joints in dissimilar materials. The variations in material characteristics necessitate designers to make adjustments on a case-by-case basis, aiming for optimal welding results.

5. Conclusion

This study focused on researching the joint strength of dissimilar materials using electron beam welding, to thoroughly explore the application prospects of electron beam welding technology under different material combinations. By analyzing the definition, characteristics, advantages, and challenges of electron beam welding, a theoretical basis for the research design can be provided. In terms of research design, this paper focuses on key steps such as material selection and material pretreatment, experimental parameter control, joint preparation and processing, and strength test methods, which were reasonably designed to ensure the accuracy and reliability of the experiment. Besides, the influence of welding parameters and material properties on joint strength was also investigated. Through the detailed analysis of these factors, a series of conclusions can be drawn, which provide strong support for the determination of the optimal parameter combinations [15]. In conclusion, this study provides a comprehensive analysis of the joint strength of dissimilar materials through electron beam welding, offering a useful reference for practices in related fields. It is anticipated that the potential of this field can be further explored in the future to promote the continuous progress of related technologies.

Disclosure statement

The authors declare no conflict of interest.

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