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Discussion on Formation and Control of Intermetallic Compounds During Welding of Different Metals

Wenbin Lu[1], Yan Zhang[1, *], Deshui Yu[1], Jianping Zhou[1], Daqian Sun[2]

[1]School of Mechanical Engineering, Xinjiang University, Wulumuqi, China
[2]Key Laboratory of Automobile Materials, School of Materials Science and Engineering, Jilin University, Changchun, China

Email address:
yanzhang4967@163.com (Yan Zhang)
[*]Corresponding author

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Abstract: The data set records the difficulties often encountered in the welding process of dissimilar metals and put forward some solutions, which provide an effective reference for the welding of dissimilar metals in the future. The connection of dissimilar metals is one of the most popular topics recently. At present, the connection methods of dissimilar metals are mechanical connection, bonding and welding. Mechanical connection can only be used in some areas with low requirements for sealing and surface smoothness because it cannot guarantee its sealing and surface smoothness. Bonding because of its poor connection strength can only be used in places where the strength requirements are not high. Since 2014, we have conducted dissimilar metal laser welding experiments on titanium (Ti)/steel and steel/aluminum (Al), and obtained more than 800 sets of data. By adjusting the welding parameters and welding process, safe and reliable joints can be obtained. A large number of studies have found that the main factor affecting the strength of dissimilar metal joints is the formation of a large number of intermetallic compound (IMCs) during welding, and most of IMCs are brittle phases. In order to further control the formation of IMCs in the process of dissimilar metal welding, we invented a new welding structure by using the special advantages of explosive welding. A large number of experiments show that the structure can effectively avoid the formation of IMCs in the welding process. In order to obtain high strength and good performance joints, control the formation of IMCs has become a key means.

Keywords: Welding, Intermetallic Compound, Dissimilar Metals

1. Introduction

With the rapid development of economy, the mechanical properties and economic value of the same material can not meet the production demand of enterprises, the use of composite materials to achieve the production demand of enterprises. It not only effectively responds to the concept of green development, but also reduces the cost to some extent. The use of composite materials can reduce the use of rare materials by replacing rare materials and conventional materials without affecting the performance, and effectively improve the utilization rate of rare materials [1- 4].

The connection of dissimilar metals has been widely used in aerospace, automobile manufacturing, medical facilities, etc. The Figure 1 shows the proportion of materials used in the manufacturing process of the Boeing 787 aircraft and Audi car body material ratio. Japan's Toyotaand and other world-famous automobile companies have vigorously studyed lightweight production technology. According to the research, if the vehicle mass is reduced by 10%, the fuel efficiency can be increased by 6%-8%, and its emissions will be significantly reduced [5-7]. Therefore, the choice of materials in automobile production process is particularly important. For example, in the design of 7 series Audi A6, its body is made of Steel/Al alloy mixed metal, and its mass is reduced by 50% compared with the front body. Steel/Al composites are widely used in cabin radiators and seat rails to effectively reduce the weight of the aircraft and reduce production costs. Due to the poor weldability of dissimilar metals and the formation of IMCs that affect the performance of the joint during welding, these have seriously reduced the range of dissimilar metals use. In broaden the use of dissimilar metals; it is necessary to improve the weldability of dissimilar metals and to avoid the formation of IMCs during welding. The reasons for the poor weldability of dissimilar metals and several measures to improve the performance of dissimilar metal joints are introduced.

(1) The weldability of dissimilar metals is closely related to their physical and chemical properties and metallurgical properties. Usually, when the physical and chemical properties of the two metals are quite different, their weldability is poor, and a large number of IMCs will be formed in the weld, which will affect the joint performance and vice versa.

(2) The base metal melted by pressure welding and brazing is less than that by fusion welding, and the IMCs formed at the joint are less, which effectively reduces the influence of IMCs on the performance of the joint.

(3) The number of IMCs formed at the joint interface when using diffusion welding and explosive welding technology to weld dissimilar metals is small. Under the same conditions, the mechanical properties of the joint are significantly improved, but the scope of application will be affected by the shape and size of the workpiece and limits.

(4) The performance of the joint can also be improved by optimizing the welding parameters, but the improvement of the mechanical performance of the joint is not obvious compared with adding an interlayer.

(5) The introduction of the third metal as interlayer in dissimilar metal welding improves the performance of the joint obviously; especially the introduction of composite interlayer can completely avoid the formation of IMCs at the joint.

(6) In addition to the above methods, the mechanical performance of the joint can also be improved by optimizing the welding structure and welding equipment in the future.

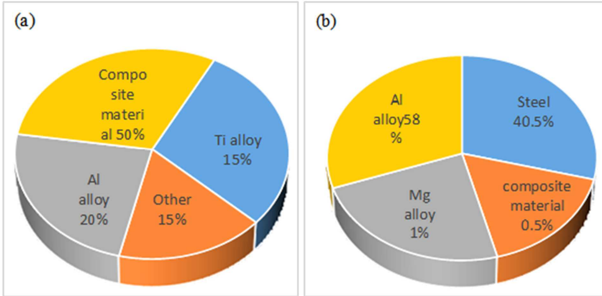

Figure 1. (a) Proportion of materials used in Boeing 787 aircraft. (b) Audi A8 car material ratio.

2. Method

2.1. Research Object

The welding of dissimilar metals will become an indispensable part of future social development. The welding of dissimilar metals can play the respective advantages of two different materials, reduce the production cost of enterprises, and avoid the excessive waste of rare metals. Therefore, it is of great significance to study the welding of dissimilar metals.

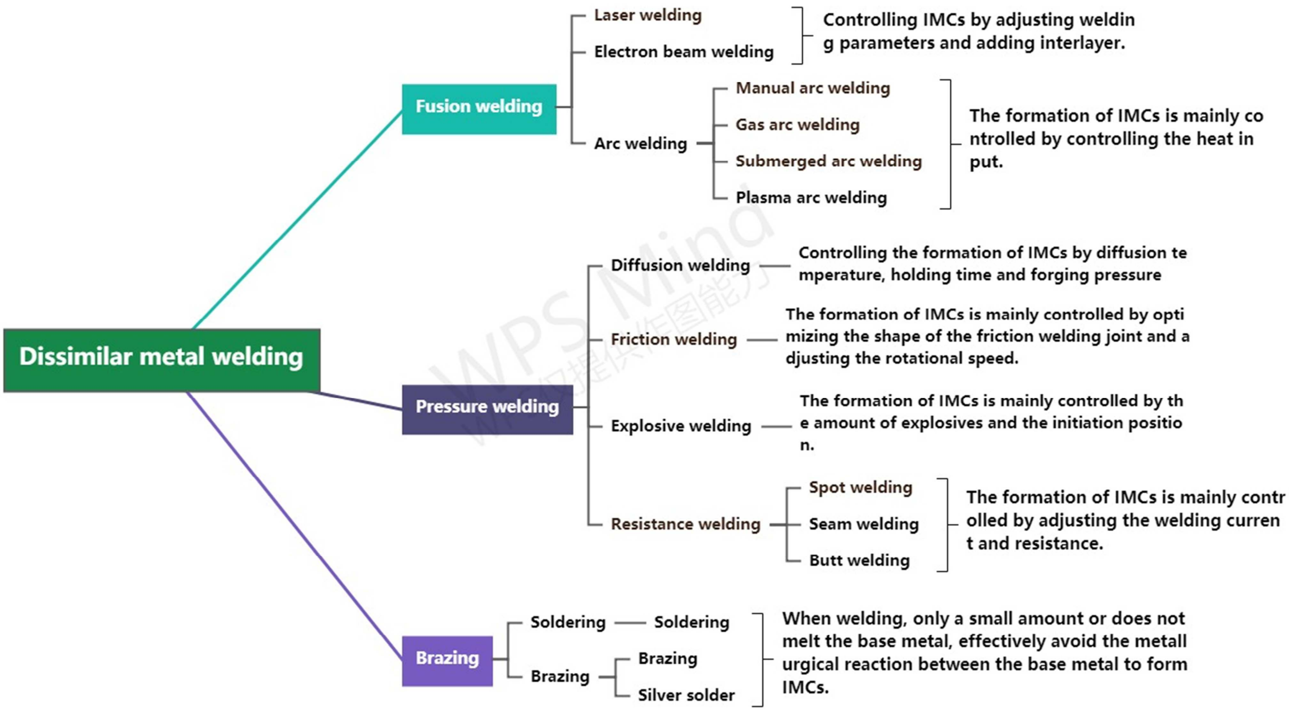

Figure 2. Main methods of dissimilar metal welding and corresponding measures to control IMCs formation during welding.

With the development of science and technology, there are more and more welding methods for dissimilar metals. As shown in Figure 2, the welding methods of dissimilar metals can be roughly divided into fusion welding, pressure welding and brazing. In fusion welding, the formation of IMCs is controlled by adjusting welding parameters and adding interlayer. The main method to control IMCs in pressure welding is to adjust welding parameters. Only a small amount of base metal is melted when brazing dissimilar metals, and the number of IMCs generated by metallurgical reactions between base metals is also small.

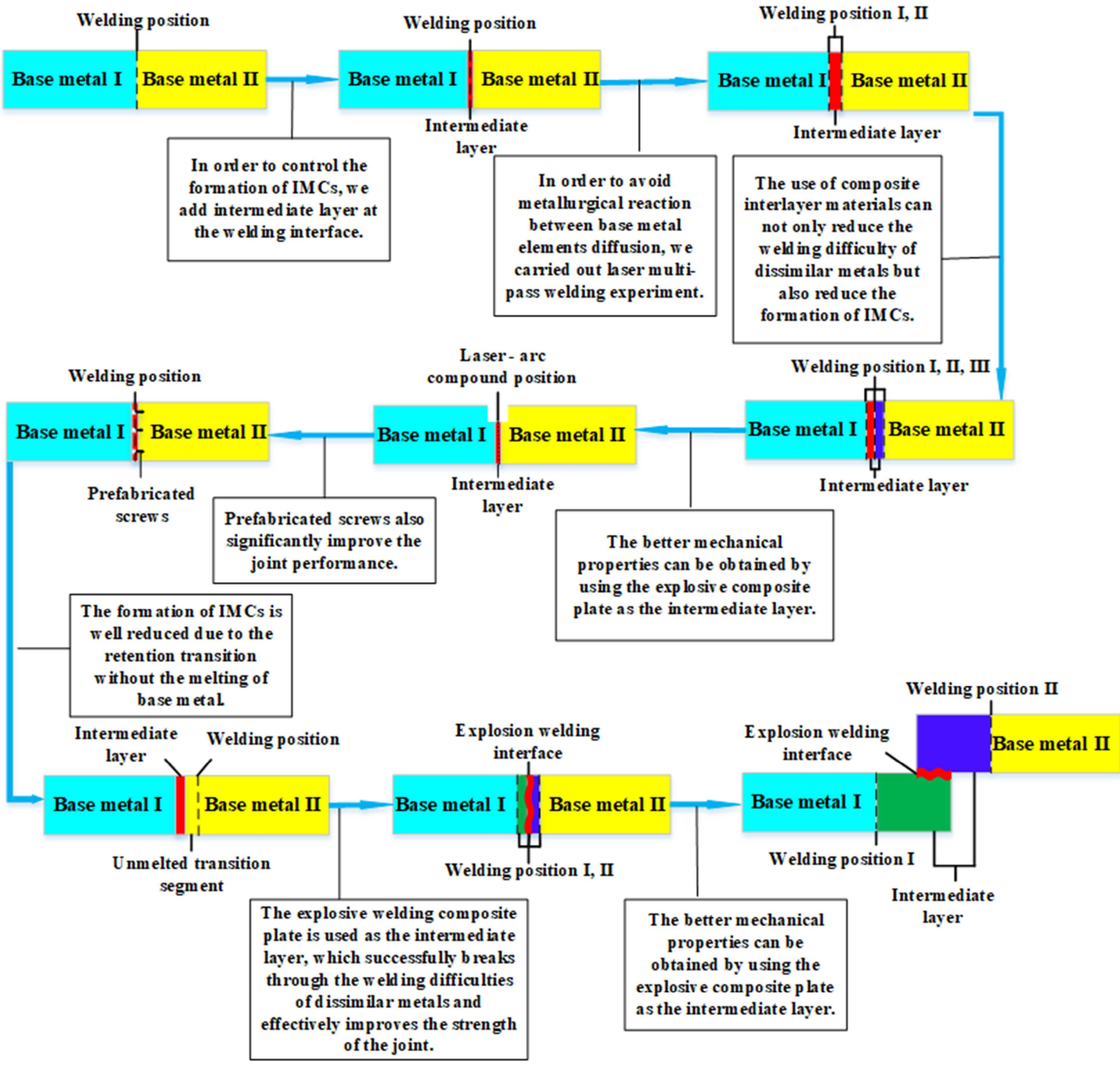

Figure 3. *Main structure of dissimilar metal welding and development course of controlling IMCs.*

Since 2016, we have carried out different metal welding and proposed a scheme to optimize the performance of the joint. Figure 3 is the main welding structure in this data set, from direct welding to adding interlayer and optimizing welding structure are to further avoid the formation of large amounts of IMCs during welding. It is found through experiments that the IMCs generated at the direct welding interface are significantly reduced after the intermediate layer is added. The effect of controlling IMCs formation by multi-pass welding is more obvious. Laser - arc series connection technology and prefabricated screw method can effectively improve the joint performance.

We also invented a more effective composite interlayer using the special advantages of explosive welding. The welding structure invented by us can effectively transform the welding of dissimilar metals into welding of the same kind of metal, successfully breaking through the problem of poor weldability due to large differences in physical and chemical properties of dissimilar metals. In the future, this welding structure will be widely used in the welding of dissimilar metal. In order to ensure the correctness of the data set information, we have done a lot of experimental demonstrations on the above welding structures [8-11].

2.2. Statement of Problem

The production of modern enterprises requires not only low cost, safe and reliable production, but also a greener production process. The welding of dissimilar metals can not only reduce the underutilization of rare metals, but also reduce the input costs of enterprises and expand profit margins. The use of composite materials is also the key to occupying the future market. Through researching, it is found that there are currently two main factors affecting dissimilar metals: (1) The physical and chemical properties are so different that weldability is poor. (2) IMCs that affecting the joint performance are generated during welding. With the rapid development of science and technology, the combination of dissimilar metals will be more widely used. Improving the joint performance and optimizing the weldability of dissimilar metals are urgent problems to be solved. In the future, the welding of dissimilar metals will be modernized and intelligent. Optimizing the weldability of dissimilar metals through special materials will become the trend of future social development.

2.3. Collection and Integration

Preparation before welding. The butt surface of the material to be welded is machined into a symmetrical plane by milling machine. The fine sandpaper was used to grind the upper and lower surfaces of the processing surface and the test plate, and the cutting marks, oil pollution and oxide film impurities were removed, and then cleaned with acetone. Since the metal interlayer is used as filler material, its cleaning is more stringent. Before welding, sandpaper with smaller particle size is used to remove impurities such as oxide film and dirt, and the flatness of the interlayer should be maintained during grinding. Then ultrasonic cleaning and drying. The thickness of the IMCs layer generated in the weld increases with the increase of heat input [12]. There by reducing the strength of the composite joint. when the welding speed is low, the heat input is large, and the consumption of the base metal on both sides is greater; when the welding speed is large, there will be no penetration phenomenon. The mechanical properties of the joint cannot be obtained. Reliable guarantee, if you want to obtain a safe and reliable joint, you should choose an appropriate welding speed.

Table 1. *Composite joints under different welding parameters.*

Material	Explain	References
Press hardened/5052 Al alloy	When 0.2 mm laser offset is selected, satisfactory welding appearance, cross-sectional macrostructural and maximum tensile strength of 129.6 MPa are obtained.	[13]
600Double molybdenum steel /6061 Al alloy	Along the weld-Al interface, the weld was surrounded by a thick irregular layer of Fe_2Al_5 phase and some randomly shaped needle-like acicular structures of $FeAl_3$ phase.	[14]
DX54 galvanized steel/EN-A W-5754 Al alloy	Compared with single-channel welding, double-channel welding can improve the appearance and corrosion resistance.	[15]

Internal collection. In the laser welding test of TC4 Ti alloy and 301 SS. When the laser beam shifts to one side of the base metal, the melting amount of the base metal on the other side decreases. The maximum strength of the joint is about 336 MPa. FeTi and $TiFe_2$ formed at the interface seriously affect the performance of the joint [16]. The CP-Ti alloy and 316 SS without filler metal were welded by laser welding. The microstructure of the reaction layer is mainly β-Ti + FeTi IMCs and the tensile strength of the joint is only 84 MPa due to the formation of IMCs [17]. Table 1 shows some welding methods for dissimilar metals and the performance of the obtained joints. Through research and investigation, it is found that in direct laser welding, the main means to control the formation of IMCs to control the reasonable heat input, cannot input too much heat.

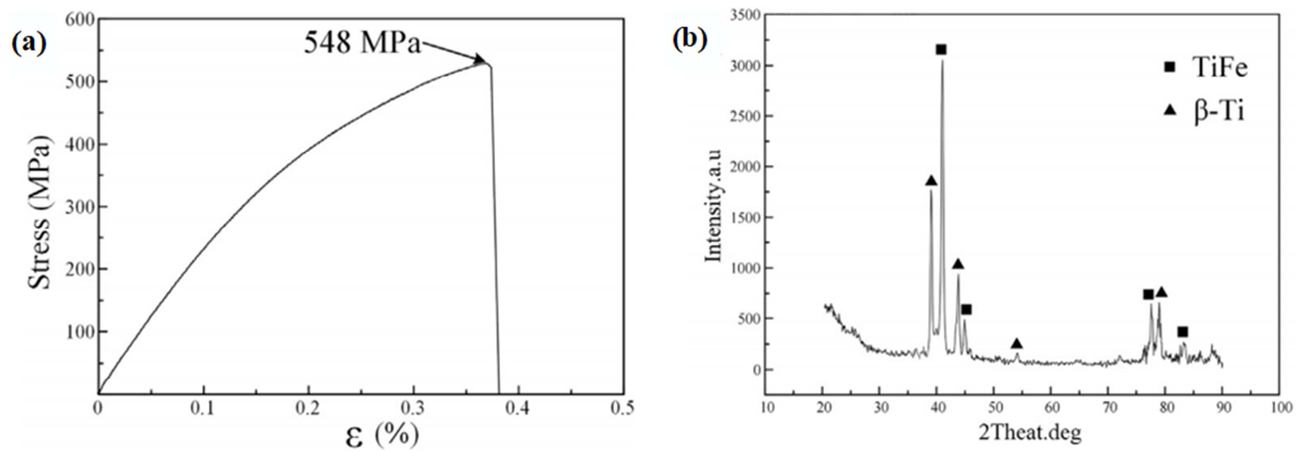

Figure 4. *(a) Tensile test curve. (b) XRD analysis results of fracture surface.*

In order to further control the formation of IMCs, we try to introduce a third metal as an interlayer. Laser welding of TC4 Ti alloy and 301 SS was carried out with Ni and Nb as composite interlayers. The laser beams are concentrated at the Ti alloy-Nb interface, Nb-Ni interface and Ni-SS interface, respectively, to ensure that the entire Nb and Ni layers are not melted. Interlayer Nb and Ni were used to prevent the formation of Ti-Fe IMCs layer and improve the microstructure and properties of Ti alloy-SS joint. The tensile strength of the joint can reach 269 MPa 18].

Double-pass laser welding of TC4 Ti alloy and 304 SS with TA2 Ti alloy/Q235 steel composite interlayer was carried out by using our invented welding structure. The unmelted composite interlayer during welding effectively prevents the diffusion and metallurgical behavior between the two metals. As shown in Figure 4a, the maximum strength of the joint is about 548MPa [19]. As shown in Figure 4b, FeTi was formed at the fracture interface, but no IMCs was formed at the welding interface, and the fracture occurred at the explosive welding interface.

***Table 2.** Add welding parameter information of different interlayer.*

Material	Explain	Reference
Q235 low carbon steel/6016 Al alloy	Presetting Si powder improves the melting state of weld pool liquidity, molten metal easy to spread at bonding interface.	[20]
DC51Dgalvanized steel/6061 Al alloy	Adding Zr powder has obvious improvement effect. The addition of Mn and Zn powders changed the element distribution, phase composition and microstructure of the steel /Al interface.	[21]
DP590 duplex steel/6016 Al alloy	The average shear strength of the steel/Al joint with Sn-5% Zr powder was 37.90 MPa, which is higher than that of the joint without Sn-5% Zr powder.	[22]

The dissimilar metal joints obtained through the welding parameters shown in Table 2 have almost no IMCs formation at the interface. In particular, the introduction of the composite interlayer improves the performance of the joint significantly and improves its weldability. Since the introduction of interlayer effectively reduces the formation of IMCs in the welding process, the strength of the joint has been significantly improved. However, due to the different diffusion rates of base metal elements at different temperatures, it is easy to make the elements between the base metals diffuse through the interlayer and then metallurgical reactions occur during welding. Through the comparison of various methods, it is found that adding a composite interlayer is the most significant method for controlling IMCs.

***Table 3.** Optimized welding method for dissimilar metals.*

Welded structure	Welding method	Strength/MPa	Explain	References
T42NG Ti/Ag95CuNiLi/ 0Cr18Ni10Ti	Brazing	220	The spreadability of $Ag_{95}CuNiLi$ filler metal on SS is poor, while the flow distance between Ti alloy and SS is greater than 100 mm, and the tensile strength of brazing seam reaches 220 MPa.	[23]
AZ31B Mg alloy/304 SS	Diffusion	57	Using Cu foil and Ni foil as interlayer can realize the effective connection of AZ31B/304 diffusion welding.	[24]
AZ31B Mg alloy/316L SS	Diffusion	57	By using pure Cu interlayer at the bonding temperature of 530°C and Ni interlayer at 510°C, the liquid phase bonding 316L SS with AZ31 Mg alloy was successfully realized.	[25]
TC4/$Cu_{37.5}Ti_{25}Ni_{12.5}Zr_{12.5}V_{12.5}$/ 304 SS	Brazing	116	The shear strength of $Cu_{43.75}Ti_{37.5}Ni_{6.25}Zr_{6.25}V_{6.25}$ foil brazed joint is 105 MPa, $Cu_{37.5}Ti_{25}Ni1_{2.5}Zr_{12.5}V_{12.5}$ foil is 116 MPa.	[26]
TC4/$Ti_{37.5}Zr_{37.5}N_{10}Cu_{15}$/304 SS	Brazing	122.14	The network structure in the joint is conducive to the release of residual stress in the brazing seam, and can improve the mechanical properties of the weld.	[27]
AZ31B Mg alloy/304 SS	Diffusion	52	In vacuum environment, the better welded joint of AZ31B / Cu / 304 SS can be obtained after holding at 530 °C for 30 min.	[28]
Al5083 Al alloy/316L SS	Friction	238	The results show that the maximum tensile strength of the joint is 238 MPa when the rotation speed is 160 mm/min and the offset is 0.4 mm.	[29]
Al6061 Al alloy/E235A steel	Friction	283	Preheating increases the peak temperature of steel, and also reduces the large temperature difference between steel and Al alloy at high temperature.	[30]

External collection. In order to improve the weldability of dissimilar metals, the appropriate welding method can be selected in addition to using the third metal as the interlayer. A large number of studies have found that other welding methods can also be used to inhibit the formation of IMCs in the welding process. For example, brazing have no or only a small amount of base metal melting in the welding process, which greatly reduces the possibility of metallurgical reaction between the base metal. Bajgholi et al. [31] used a zirconium-based interlayer for the brazing of TC4 Ti alloy and 316L SS, the large amount of Ni-Ti IMCs were generated in the brazed joint. The hardness of the joint center was about 500 HV. It was higher than that of the base materials on both sides. Yue et al. [32] conducted vacuum brazing using Ag-Cu alloy as the brazing filler metal, result showed that the joint was comprised of CuTi, Ag- rich, Cu_4Ti and β-Ti phases. The strength reached 188 MPa. However, high temperature caused the Ag-rich liquid phase to flow out of the joint. The Ag-rich region was replaced by a large amount of brittle Ti-Cu phase, which reduced the welding quality. Long brazing time caused the Ti-Cu IMCs to grow excessively.

Explosion welding can improve the performance of joints by using unique wavy joints. Li et al. [33] conducted the welding test of 1060 Al plate and Q345 swallowtail groove steel plate by using explosive welding technology. The results show that the combination form of aluminum plate and swallowtail fish tank steel is better than that of ordinary explosive welded joint, and the explosive amount is significantly reduced. The average tensile strength of the joint is 531.9 MPa, and Al side fracture occurs in the shear test. Liu et al. [34] conducted explosive welding test with A1050 Al and Q235 steel. It was found that the wave shape at the welding joint was similar to the sinusoidal image, and the Fe and Al elements diffused each other. The Fe-Al IMCs formed at the joint included Fe_3Al, FeAl, Fe_2A1_5 and Fe_2A1_7. The tensile strength is 343 MPa, the shear strength is 80 MPa. Table 3 introduces the welding methods of dissimilar metals. These data are also one of the contents of this data set, and also provide a reference for the welding of dissimilar metals in the future.

2.4. Data Record

The first Data Record (DOI: 10.5281/zenodo.5461104) is a document contains two types of research reviews written by this research group.

1) The SEM image of Ti/TiNi joint with laser centering welding.
2) The OM images and tensile strength.

This study realized the joining between TiNi and Ti alloy, and got the TiNi/Ti composite plate. TiNi shape memory alloy has good superelasticity to correct the dislocation teeth, and Ti alloy has good specific strength to support the supporting teeth. So the TiNi/Ti composite plate is suitable to make dental arch wire. The research method of this group aims to explore the joining principle between different materials, find the application scenarios of different materials joining, and provide theoretical support for subsequent material joining research.

This record contains all the reliability analysis tests and the inter-item Spearman correlation matrix results.

3. Technical Validtion

3.1. Macro and Micro Analysis

After laser welding, when the specimen is cooled to room temperature, the metallographic specimen is taken out in the middle of the weld by wire cutting. Then clean up the oil stain and cut marks on the surface of the sample, and insert them into metallographic samples with a certain size through resin and mold. The metallographic samples were polished with 360 # ~ 3000 # metallographic sandpaper until there was no obvious scratch on the surface of the sample. Then the metallographic specimen is polished until the surface of the specimen becomes mirror. Subsequently, the metallographic sample was subjected to chemical corrosion, and after the corrosion, the surface of the sample was washed with water and alcohol, respectively, and then dried. The microstructure of the joint was studied by ScopeAxioZEISS optical microscope and S-3400 scanning electron microscope (SEM), and the composition of the microstructure was analyzed by EDAX spectrometer. The samples were intercepted in the middle of the weld, and the phase composition of the joint was analyzed by X'Pert3Powder micro-area X-ray diffractometer (XRD). The JEM-2100F transmission electron microscope (TEM) was used for observation, and the microstructure characteristics of the joint were further revealed through the calibration of the open field image and the selected area electron diffraction pattern.

3.2. Fracture Analysis of Weld

The fracture morphology was observed by SEM to determine the fracture type of the joint. The chemical composition of the fracture characteristic region was determined by energy dispersive spectrometer (EDS, INC), and the microstructure of the fracture region was analyzed. The phase of the fracture was analyzed by XRD, and the composition phase of the fracture was finally determined.

3.3. Microhardness Test

The microhardness distribution of each region of the joint was tested by MH-3 microhardness tester. The test position of hardness test is in the middle of the sample. During the measurement, three groups of data were collected along the direction perpendicular to the weld seam, and the average value of the three groups of data at each position was taken as the hardness value of this point.

3.4. Tensile Strength Test

The tensile properties of joints were measured by MIS8/0.22M electro-hydraulic servo material test system. The mechanical properties are characterized by tensile strength Rm (MPa), that is, the maximum force of the specimen during tensile fracture is divided by the original cross-sectional area of the specimen.

The joints obtained from this data set are tested by mechanical testing. It can be found that the performance of the joints can meet the requirements by optimizing the structure and adjusting the welding parameters. And China began to accelerate the application of heterogeneous metals in the past few years. Sinopec company used Ti/Steel composite plates (Q235R+TA2) to make a large ethylene glycol reactor tower with a mass of about 89.4t, which improved the utilization rate of resources to a certain extent. The welding of dissimilar metals is widely used in China. Due to the formation of a large number of IMCs during welding, the joint performance is seriously deteriorated, which cannot meet some places with high strength requirements. This dataset provides a large number of methods that can effectively avoid the generation of harmful metal gold compounds in the welding process, which lays a solid foundation for the future use of dissimilar metals.

4. Conclusion

Comparison of the different welding methods showed that fusion welding joints had relatively high strength and flexible welding size. By heat source and using intermediate layer, the content of IMCs in the weld could be reduced. However, IMCs could not be completely avoided. Thus, how to effectively avoid the formation of IMCs remains the focus of research, including controlling heat input more precisely or finding more suitable intermediate layers to improve the mechanical properties of the dissimilar metals joints. They could provide a theoretical basis for improving the welding of dissimilar materials. The high hardness and low toughness of IMC the main problem on welding dissimilar metals.

Increasing the welding speed, the temperature gradient and the decreasing rate of the molten pool reduces the heat input during the welding process and the thickness of the IMC layer could be reduced.

Usage Notes

The available data can be used for laser welding of Ti/steel, steel/Al and Ti/TiNi, and can also provide reference for welding of other metals and some measures to improve the performance of joints. However, the welding parameters should be appropriately adjusted according to the different equipment used.

Conflict of Interest

All the authors do not have any possible conflicts of interest.

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