Research progress in friction stir welding of steel and aluminum

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Abstract. Only by obtaining a good comprehensive performance of steel/aluminum dissimilar metal joints can the steel/aluminum dissimilar metal joint structure be used more widely in the field of national defense and national production. However, cracks and intermetallic compounds are easy to occur during welding of steel/aluminum, which seriously affects the quality of welded joints. As a kind of low temperature and high efficiency solid phase bonding method, friction welding has been attached great importance in the field of new material connection and high performance equipment manufacturing. Among friction welding methods, the friction stir welding has been paid more and more attention because of various types of welded joints. In this paper, the research progress of friction stir welding of steel/aluminum is introduced from the form and process parameters, which provides the basis for further research.

1. INTRODUCTION
The connection of dissimilar metals has been a hot topic in modern manufacturing industry, especially with the properties of complementary, low melting point metal in Aluminum Alloy as the representative of the low density, fast heat conduction, and high melting point metal such as stainless steel with corrosion resistance, high temperature oxidation resistance and high strength composite connection technology is the focus of attention¹-³. Aluminum is light weight, with good electric conductivity and thermal conductivity, corrosion resistance, easy extension, recyclable and other excellent physical and chemical properties, and the development of the steel has been nearly one hundred years history, aluminum and steel is the most widely recognized as the basic metal materials used. The connection of dissimilar materials between aluminum and steel structure has good comprehensive properties of two kinds of materials, can effectively reduce the quality of structure, and has high strength and excellent corrosion resistance; the material is saved, but also improves the reliability of the structure, and in the aerospace, nuclear industry, space technology, microelectronics, automotive, petrochemical and other fields has been widely used. Such as the United States Delta IV rocket tank manufacturing, Japan's H2B rocket propellant tank, propeller duct structure, heat pipe structure, neutron detectors, particle accelerators are related to aluminum and stainless steel welded structure. However, in terms of thermal physical properties such as melting point, thermal conductivity, coefficient of thermal expansion, etc. or in material mechanical properties, heterogeneous metal lead to connection difficulties, poor joint properties, which has always been the core point of the research.

Friction stir welding is a new type of solid phase bonding technology, which is developed by TWI in
1991, it is suitable for various structure materials with homogeneous or heterogeneous, has been widespread concern since the advent of FSW\cite{4}. The principle for the stirring head in the axial pressure and the workpiece in close contact, by rotating the mixing head and the workpiece between the heat generated by friction of the metal soften, the pin in mechanical agitation under metal flow and mixing head along a certain direction, forming a joint. The principle is the stirring head in the axial pressure and the workpiece in close contact, the metal is softened by the heat generated by the friction between the rotating stirring head and the workpiece, and the metal flows in the stirring direction of the stirring needle, forming a joint. The advantage of FSW is mainly manifested in the process margin, allowing the butt gap tolerance 0.1t (t thickness); apparent good weld after welding, smooth surface, no obvious bulge and the weld welding drops, without subsequent surface treatment; good mechanical properties, fatigue, fracture and bending performance are better than the melt welding, the isotropic mechanical properties of the joints\cite{5}. Because of the above advantages of FSW, the invention of FSW immediately set off an upsurge of research, and soon was put into industrial applications, the relevant mechanism is also more and more attention. In this paper, the research progress of friction stir welding of steel/aluminum is introduced from the form and process parameters.

2. STEEL/ALUMINUM FSW JOINT TYPE
In general, the friction stir welding method can be used to achieve the joint form as shown in Figure 1. The most basic form of joint is butt and lap joint, respectively, as shown in Figure 1a and figure 1d, the other types of joints can be formed by the combination of these two types of welding.

2.1. Steel/aluminum FSW butt weld technologies
For the steel/aluminum dissimilar metal friction stir welding, because the melting point difference (Aluminum Alloy is about 600 degrees Celsius, the steel is about 1400 degrees Celsius), in order to prevent overheating of the aluminum side, using the method of mixing tool offset, the center line of the mixing head toward the aluminum side, there is still a small pin can come into contact with steel the matrix, in order to achieve the deformation of the steel side. Liu et al\cite{6} by this method to realize the connection of 6061-T6 and TRIP high strength steel 780/800, shown in Figure 2 for welding assembly drawing and cross sectional views of FSW, we can see that the 'Tool offset' is the mixing head is offset from the center line of weld center distance.

2.2. Steel/aluminum FSW lapping process
The idea of using FSW to prepare the overlapping joints of dissimilar metals has been proposed by many researchers, and a lot of experiments have been done. In 2007, Chen et al\cite{7} first prepared the lap joint of AC4C cast aluminum alloy and AZ31 magnesium alloy by FSW, in the premise of pin does not contact the bottom of AZ31 magnesium alloy, AC4C aluminum and magnesium alloy AZ31 can be welded successfully. Later, Chen et al\cite{8} studied on friction stir lap of AC4C cast aluminum and zinc coated steel, was also in the pin does not contact the metal bottom, connected by an intermediate interface reaction layer to achieve the highest joint strength was 50 MPa. Similarly, the friction stir lap joints of ADC12 aluminum alloy and pure titanium were successfully obtained, and the tensile strength of the joint was up to 62% of ADC12 aluminum alloy\cite{9}.
It can be found that the welding strength cannot be improved effectively when the needle is not connected with the bottom metal in the aluminum/steel dissimilar lap experiment. Xiong et al.\cite{10} and Wei\cite{11} proposed by cutting the pin, designed the stir head formed by a concave shoulder (material for high speed steel W18Cr4V) and a cutting stirring needle (hard alloy rotary file, standard parts), studied the FSW lap joints of 1060Al and 1Cr18Ni9Ti stainless steel, and tensile shear strength reached 95 MPa, the tensile strength of more than the Al of the parent material, the fracture location in friction stir lap HAZ of aluminum. The structure and composition of the cutting needle is shown in figure 3.

3. STEEL/ALUMINUM FSW PROCESS PARAMETERS

3.1. stir head
The stir head is the core component of the FSW process, and its design is one of the most important processes in the FSW process. The advantages and disadvantages of the mixing head determine whether the FSW process can expand the types of materials to be welded and the thickness of the material to be welded, and also the prerequisite for FSW to obtain high quality joints\cite{12}. The domestic and foreign literatures have some comprehensive discussions about the design of the mixing head, but because of the secrecy of the welding method, the detailed design principle is unknown. The mixing head is mainly composed of two parts: the shaft shoulder and the stirring needle. The size and shape of the stirring head determine the size of the weld, the welding speed and the strength of the joint; stirring head material determines the friction heating rate, stirring head strength and welding temperature, welding temperature determines the range of FSW welding materials\cite{13}. 

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3 Schematic diagram of FSW test assembly
4 Cross sectional view perpendicular to weld

Fig.2 Schematic of the FSW configuration view perpendicular to the weld line (unit: mm)
The 2 main functions of the mixing head in conventional FSW are to generate heat and to make the material flowing deformation. The primary source of heat is the friction between the stirring pin and the workpiece when the stirring head is first screwed in, other heat comes from the deformation of the material. The stirring head is screwed with the workpiece, until the tool shoulder and the workpiece in close contact, friction of shaft shoulder and the workpiece have great heat. The second function of the mixing head is to stir and move the material. Therefore, the design of the stirring head also determines the rules and characteristics of the material after processing.

### 3.2. process parameters

The stirring head speed (r/min) is one of the main factors affecting the FSW heat source, when the speed is low, the frictional heat generated is not enough to make plastic materials, solid connection cannot be realized; with the increase of rotational speed, the friction heat increases gradually, and the plastic flow layer increases gradually from top to bottom, the hole gradually decreases until it disappears, forming a dense mixing zone. High speed will cause the material around the needle and the shaft shoulder overheating, affecting the formation of weld. According to the processing material, plate thickness and welding speed, the speed is usually between 200~2000r/min\[14\]. The welding speed (V, mm/min) is the speed of the stirring head moving forward in the friction stir processing. If the welding speed is too low, the heat generated by the mixing head makes the welding temperature too high, the temperature of the metal in the nugget zone reaches or exceeds the melting point, which is easy to produce the crack, if the welding speed is too high, the heat generated is not enough to make the metal around the stir head to achieve the plasticizing state, therefore, should be based on the material to be welded, plate thickness and speed to choose the appropriate welding speed\[15\].

The input of heat mainly depends on the ratio of rotational speed and welding speed, if the ratio is too large, the heat input near the melting point of the material to the weld metal is too plasticizing, influencing the weld metal flow, can not form a good joint. A large number of research results show that increasing the heat input will increase the thickness of the steel/aluminum intermetallic layer, and significantly reduce the performance of the welded joint. In addition, when the rotation speed is low or
when the welding speed is high, weld heat input is small, around the pin material (especially steel side) without sufficient plasticization, unable to realize the friction stir welding of aluminum and steel, may be point contact connection and other defects. At present, in the research of friction stir welding of aluminum and steel, the main process parameters are different according to different materials.

Liu et al.[6] studied the FSW of 6061-T6 and TRIP 780/800. The optimized process parameters were 1800 r/min and welding speed of 60 mm/min. And found that the welding speed on the welding pressure, temperature distribution, strain rate and the intermetallic compound layer has significant influence, but the welding speed is too high will shorten the cycle of high temperature, so the thickness of compound layer decreases; increase of rotational speed, can significantly improve the temperature distribution of the whole joint, reduce the axial and radial mixing head forward resistance that could also affect the thickness of compound layer. Ramachandran et al.[16] studied the FSW process of AA5052 aluminum alloy and HSLA steel under the condition of changing the welding speed, when the rotating speed is constant, the appearance of the weld is different at different welding speed. At 40 mm/min, the weld formation is the best, shown in Figure 4.

4. PROSPECTS
Because the aluminum and steel are easy to form brittle intermetallic compounds, as well as the aluminum alloy surface stubborn oxide film, making the connection of aluminum and steel has great difficulty. Friction stir welding by friction extrusion can effectively remove the oxide film on the surface of Aluminum Alloy, can better control the thickness of the brittle material layer between two materials, especially suitable for welding between Aluminum Alloy and steel plate parts. At present, the friction stir welding method, can realize the aluminum / steel butt and lap welding in the good. By optimizing the process parameters, the strength of the joint is equivalent to the strength of the aluminum base material. However, the control of intermetallic compounds in the interface needs to be further studied in order to ensure the best performance.

Acknowledgement:
Project: 2017 Anhui university natural science key research project, project number: KJ2017A750

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