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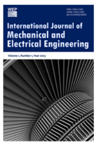


Research Status of Friction Interface Evolution Mechanism of Non-magnetic Steel

Tiantian Xue

School of Materials Science and Engineering, Xi'an Shiyou University, Xi'an 7100652, China

ABSTRACT

The non-magnetic drill pipe (composed of male and female thread joints and rod bodies) is the key component of the directional drilling technology equipment for gas extraction in coal mine tunnels. The thread joint and the drill pipe body are connected by continuous drive friction welding. In the study, it was found that the banded structure appeared in the joint of continuous drive friction welding of non-magnetic steel, which reduced the strength of drill pipe. At the same time, it is found that the heat flow mode is one of the key factors affecting the banded structure, and the heat flow mode is based on the evolution of the interface plastic ring. In this paper, through the review of the research status of the interface evolution law of non-magnetic steel continuous drive friction welding, the experimental method for the study of the interface evolution law of non-magnetic steel continuous drive friction welding is found.

KEYWORDS

Non-magnetic Steel; Rotary Friction Welding; Corona-bond.

1. INTRODUCTION

The most basic requirements of non-magnetic drill pipe raw materials are permeability less than 1.005 and yield strength higher than 1000 MPa. The Cr-Mn-Ni-Mo-N type non-magnetic steel just meets the basic conditions for manufacturing non-magnetic drill pipes. The non-magnetic steel belongs to the high-strength austenitic stainless-steel category. The steel is based on solid solution strengthening (high content of nitrogen alloy elements, especially Ni, up to 21%) and deformation strengthening (repeated forging) mechanism to achieve its strength improvement. Non-magnetic steel is not only used in the manufacture of non-magnetic drill pipe, but also widely used in ten areas of national strategy. However, there is no report on friction welding of non-magnetic steel at home and abroad. Therefore, the research results of friction welding of high strength austenitic stainless steel can be used for reference. From the perspective of the composition of non-magnetic steel, it not only contains a high content of alloy components (such as: Cr, Mo, Ni, Mn, etc.), but also contains a high content of N element, which also belongs to high nitrogen austenitic stainless steel.

The application field of friction welding is very extensive. Many parts in industrial production are processed by friction welding. The application of friction welding in developed countries began earlier, so the technology is very mature. They have been able to use inertial friction welding to weld aero-engine powder metallurgy turbine discs and shafts. Linear friction welding has been successfully applied in the manufacture of aircraft engine blisks with high thrust-to-weight ratio. As an important welding method in the field of aircraft manufacturing, friction stir welding is widely used in the production of large aluminum alloy parts. German MTU is studying the friction welding technology of high-pressure compressor rotor and other large parts. Friction welding is generally considered to be a reliable and reproducible welding technology. In aircraft manufacturing, friction welding also provides prospects for new applications. AISI4340 ultra-high strength steel has high notch sensitivity and is prone to welding embrittlement. When used in the manufacture of aircraft landing gear, friction welding is used between the landing gear and the pull rod. Therefore, the application and development prospects of friction welding have been paid more and more attention. More and more researchers have done a lot of research on the application development and process optimization of friction welding [1].

2. RESEARCH STATUS OF FRICTION WELDING

For many years, friction welding has been favored by the manufacturing industry for its high quality, high efficiency, energy saving and pollution-free technical characteristics, and has received extensive attention and attention worldwide. Compared with traditional welding methods, its main advantages are as follows [2].

(1) Good welding quality. One. In general, friction welding does not need to be filled with materials. During the welding process, the welded sample does not melt because the friction heat does not reach the melting point of the material, so it will not produce defects caused by the melting of the base metal. During the welding process, the microstructure of the welding zone is forged due to the effect of the upsetting force. These conditions will improve the performance of the joint, making the weld performance close to the base metal or even more than the base metal.

(2) High production efficiency. The whole process of friction welding is very fast, generally speaking, the duration of the whole welding process is very short between one minute and a few seconds. In the welding process, the welding efficiency will be greatly increased by adding welding auxiliary equipment. According to a report, a company in the United States used inertial friction welding to weld the aero-engine compressor disc. The entire welding process was very fast and lasted only three seconds [3].

(3) Wide process adaptability. For friction welding, both the same material and different materials can be welded. The physical properties of some weldments are quite different, and the weldability is not good. The traditional welding method cannot obtain the normal service welding joint. But for friction welding can be welded [4].

(4) The reliability of the welding process is high. Friction welding equipment is simple, because the welding process is fully automatic to exclude human uncontrollable factors, and the welding parameters are few, so it can ensure the unity of the quality of welded joints [5].

(5) Low cost, low energy consumption, environmental protection and safety. Friction welding consumes less power than traditional welding methods, thus saving energy and reducing investment, and friction welding does not need to process the weldment groove in advance, saving the time and investment required for processing [6].

(6) High machining accuracy. Before welding, the standard assembly and accurate positioning of the weldment can be guaranteed, so the accuracy of welding processing will be very high.

In the welding process of continuous drive friction welding, the friction heat generated by the relative motion between the welding contact ends makes the contact surface and its adjacent area heated to the viscoplastic state. This viscoplastic state provides sufficient fluidity for the material, resulting in the required macroscopic plastic deformation. Subsequently, through the rapid and accurate upsetting operation, the close combination of the welding interface is ensured, and the whole welding process is successfully completed.

Fig.1 summarizes the characteristics of plastic ring evolution in the friction welding interface welding process [7-12], and divides the friction welding process into three stages:

The first stage is the initial ' heating stage ' of friction welding where the torque and temperature both show a gradual upward trend, and the interface gradually heats up to the appropriate welding temperature point. As the temperature continues to rise, the metal on the friction interface gradually plasticizes and forms a plastic ring, thereby achieving the purpose of welding [7,10,11]. At the end of the first stage of friction welding, the plastic ring has completed its nucleation process and successfully extended to the entire welding interface, thus laying a key foundation for joint forming [13-17].

The steady-state extrusion stage is the second stage of friction welding, in which the torque and temperature maintain a relatively stable equilibrium state. During the welding process at this stage, high-temperature thermoplastic metals are continuously produced at the interface, and these metals are then squeezed out of the interface to form a flash phenomenon. In this regard, the research of Xiong Jiangtao [18] and Li Wenya [19] and other scholars conceptualized this phenomenon as the formation and evolution of the plastic ring, that is, the plastic ring covers the entire welding interface and is squeezed out under the applied welding pressure.

The third stage is the upsetting and cooling stage. This process essentially represents the transformation process of the plastic ring morphology at the friction interface to the evolution of the heat flow mode.

In summary, starting from the analysis of the formation mechanism of the joint structure, the core essence of the continuous drive friction welding process can be summarized into the following three aspects: the nucleation of the plastic ring, the subsequent evolution process, and the formation of the final heat flow mode. The research work of this paper will focus on these three key interface evolution links, aiming to reveal their internal laws and formation mechanisms.

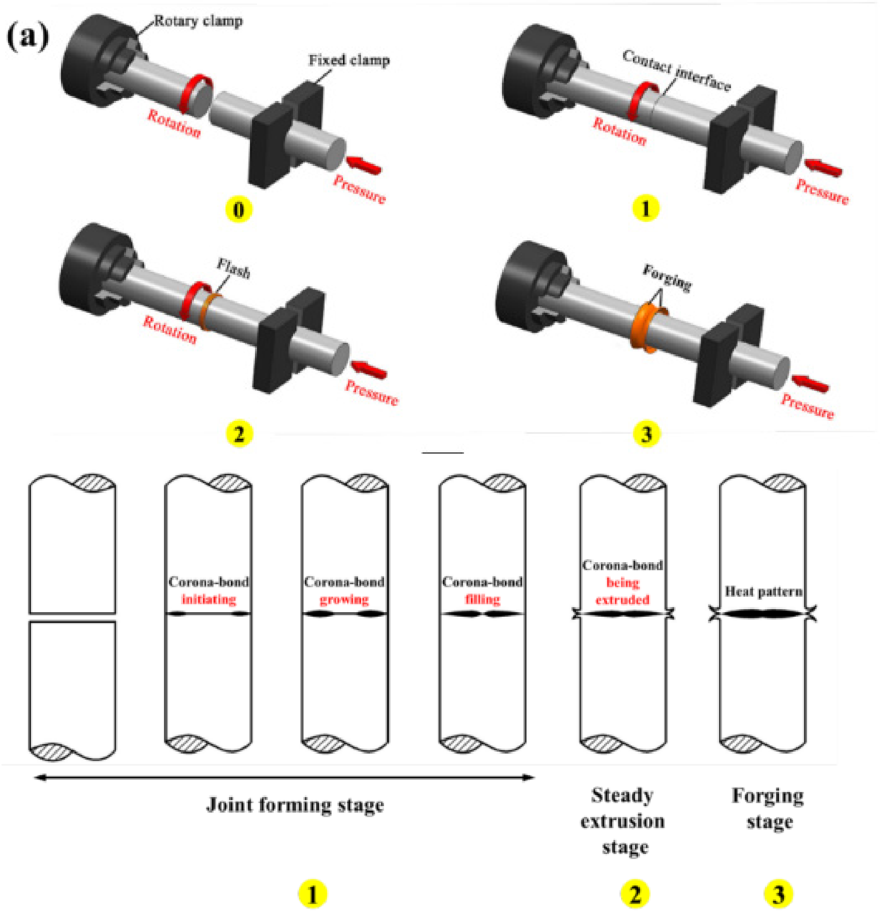


Fig 1. Division of three stages of interface welding process of rotary friction welding [22-28]: (a) Process; (b) Schematic diagram of interface morphology evolution

At present, the research on friction welding of high nitrogen austenitic stainless steel is mainly focused on friction stir welding [20-24], while the research on continuous drive friction welding is relatively less [24-26]. Reviewing the existing literature, friction stir welding has the characteristics of rapid temperature change and high-strength friction and large deformation, and the strength of the joint is not lower than that of the base metal. On the contrary, in the preliminary study of the field of continuous drive friction welding [25-26], it was found that the yield strength of the continuous drive friction welded joint was about 75 % of the base metal.

3. LITERATURE REFERENCES

3.1. Research Status of Interfacial Plastic Annular Nuclei.

The heat flow mode [25] is derived from the concept of the American Society of Metals (ASM) [26]. It refers to the envelope formed by the microstructure change area caused by the welding thermal cycle during the friction welding process. In continuous drive friction welding, this envelope is mainly composed of shear deformation regions formed by shear deformation.

Hasegawa [12] systematically discussed the regulation effect of welding pressure on the position of plastic annular nucleus from the experimental level for the first time. The experimental results show that when the pressure gradually increases from 5.5 MPa to 35 MPa, the position of the plastic ring core gradually moves from the center of the joint to 1/2 R in the radius direction. However, when the pressure further increases to more than 35 MPa, the position of the plastic annular nucleus tends to be stable, basically fixed at 1/2R, and no obvious displacement occurs. This finding not only reveals the intrinsic relationship between the pressure and the position of the plastic annular core, but also points out its limitations in practical applications.

In the study of Kimura [13,15], the influence of rotational speed on the position of plastic ring nucleus in friction welding process was deeply discussed. The position changes of the plastic annular nucleus under different rotational speeds were compared experimentally. The experimental results show that the plastic annular nucleus mainly appears at the outer edge of the bar at high rotation speed. At low rotational speed, the nucleation position of the plastic ring is relatively random, which may appear at any position between 1/3 and 3/4 of the radius of the specimen. However, due to the limited amount of data, it is still difficult to form a complete and systematic law. In addition, Kimura [15] also discussed the effect of friction pressure on the plastic ring, and found that the plastic ring nucleus moves from the center to the outer edge under ' low friction pressure ', while under ' high friction pressure ', the plastic ring nucleus is mainly located at the outer edge. These studies provide an important experimental basis for understanding the evolution of plastic ring nuclei during friction welding.

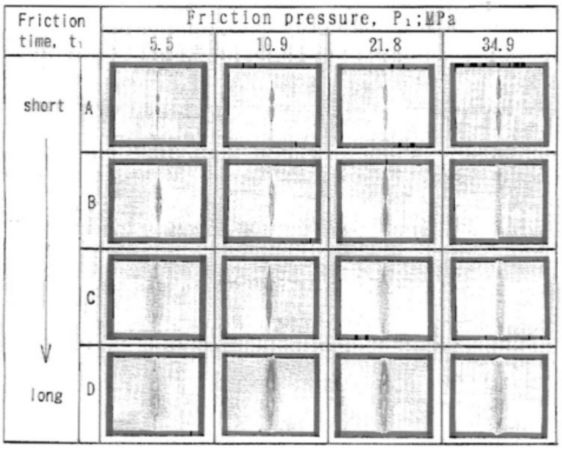
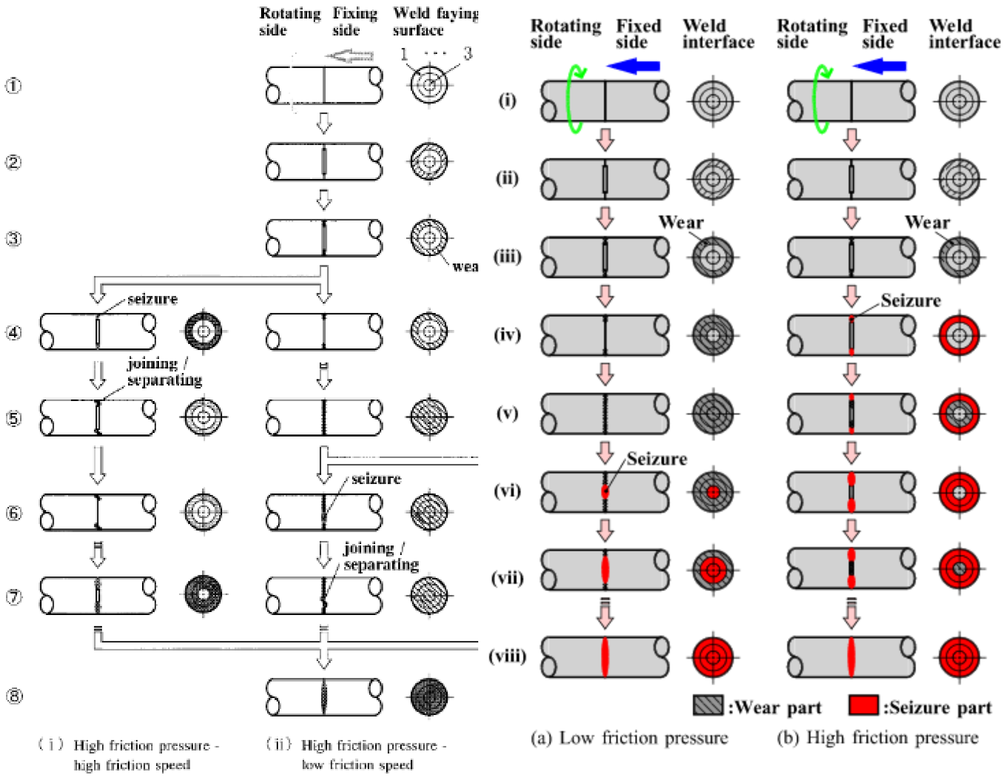


Fig 2. Experimental results of Hasegawa [12] on the position evolution of plastic toroidal nuclei



（ i ） High friction pressure - high friction speed
（ ii ） High friction pressure - low friction speed
(a) Low friction pressure
(b) High friction pressure

Fig 3. Kimura [13,15] Experimental results on the position evolution of plastic toroidal nuclei

The research system of Li [17] explored the influence of rotational speed on the position of plastic annular nucleus. In this study, 20# solid steel rod was used as the experimental material. Firstly, a constant pressure of 40 MPa was set, and a series of speed ranges were set from 900 rpm to 2100 rpm. The corresponding outer edge linear speed was between 1.17 m/s and 2.74 m/s. The experimental results (Fig.4) show that with the increase of welding speed, the position of plastic ring core gradually moves from the outer edge of the steel bar to the midpoint of the radius (i.e., 1/2R). When the rotational speed exceeds a certain threshold (1200 rpm), the position of the plastic ring nucleus tends to be stable and is always located at 1/2 R of the midpoint of the radius. In addition, the evolution of the width of the plastic annular nucleus with the change of welding speed was also discussed. The results show that with the increase of rotational speed, the width of plastic annular nucleus shows an obvious widening trend. The steel bar with a diameter of 25 mm was taken as the research object. When the welding speed was increased to 2100 rpm, the width of the plastic annular nucleus experienced a steady expansion from the initial 0.5 mm to 0.8 mm. Nevertheless, the current complete understanding of the width evolution of plastic toroidal nuclei still has limitations and needs to be further improved in order to construct a more comprehensive description framework.

Jin [27-28] et al. conducted in-depth research on the friction interface heat generation distribution of different materials in rotary friction welding, and specifically analyzed the plastic ring nuclei and evolution of austenitic alloys such as SUS304, GH2132 and GH4169. The distribution model of friction heat generation was established. Based on this model, the mathematical model of the evolution of the position and width of the plastic ring core with the welding process was further constructed, and the internal mechanism of the plastic ring expansion was deeply analyzed. The results show that for materials with poor red hardness (such as SUS304), the plastic ring mainly nucleates at 2/3R position, and the nucleation position is less affected by the rotational speed. However, the nucleation width increases with increasing rotational speed, from 0.4 R at 500 rpm to 0.7R at 2000 rpm. In contrast, when the red hardness of the material is higher (such as GH2132 and GH4169), there is a critical rotation speed of 900 rpm. When the rotational speed is 900 rpm, the plastic ring also nucleates at 0.33R ~ R, and then expands with the welding process until the entire friction interface is covered. When the rotational speed is 900 rpm, the plastic ring nucleus is close to the 0~0.33 R of the central region. At this time, there is a criterion for the width of the plastic ring nucleus: for GH2132 with less red hardness, the nucleation width is 0.4R, which can still be expanded; for GH4169 with larger red hardness, the width is 0.4R, and there is no expansion phenomenon.

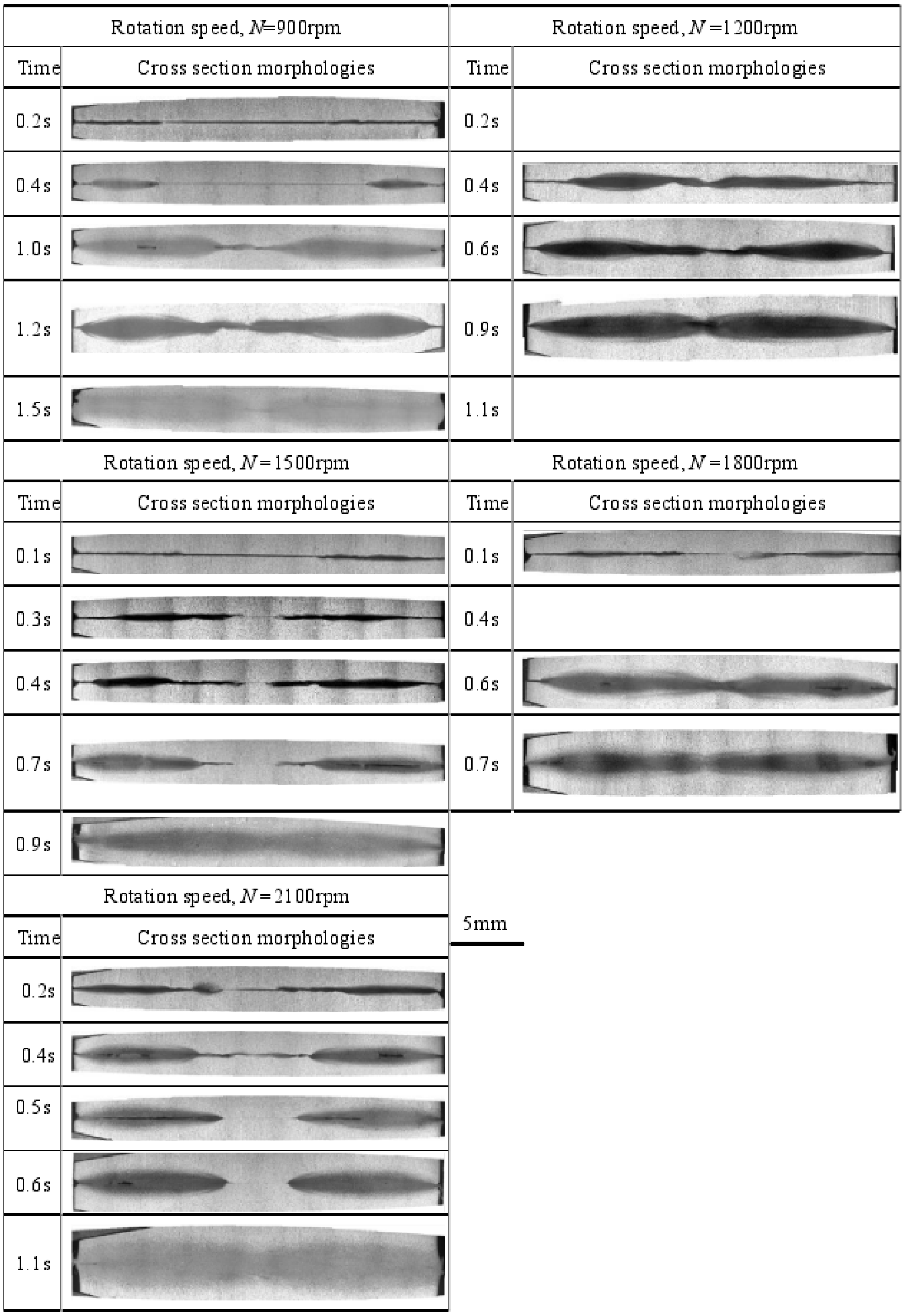


Fig 4. Experimental results of Li [17] on the evolution of plastic toroidal nuclei with time

Jin [27-28] conducted continuous drive rotary friction welding experiments on SUS304 stainless steel rods with a diameter of φ25 mm, and conducted in-depth research under multiple welding pressures, rotational speeds, and friction time conditions. Focusing on the friction interface, the evolution of the interface stress distribution was systematically measured, and the evolution of the plastic ring (i.e., the plasticized metal region) and the interface pressure distribution was characterized in detail. The experimental results (Fig.5) show that under the constant welding pressure, the interface stress is mainly concentrated in the outer region of the sample interface, resulting in the formation of a ' virtual contact ' state in the internal region at the initial stage of friction. Subsequently, the normal stress gradually expands along the radial direction, showing a ' U ' -shaped distribution. Under the combined influence of pressure and friction linear velocity, the stress growth rate of the outer edge region of the interface is significantly faster than that of the inner region, which makes the stress distribution change into a ' V ' shape. As the friction process continues, the stress in the central region gradually increases, and its distribution pattern gradually changes from ' V ' to ' M '. Finally, the stress distribution tends to be uniform. This evolution process is closely related to the evolution of the corona bond. When the plastic ring covers the entire interface, the interface pressure distribution exhibits approximately uniform characteristics. In addition, the experiment also found that under different welding parameters, the interface stress distribution and the evolution of the plastic ring have similar characteristics. This finding provides an important basis for further understanding the relationship between interfacial stress distribution and plastic ring evolution during continuous drive rotary friction welding.

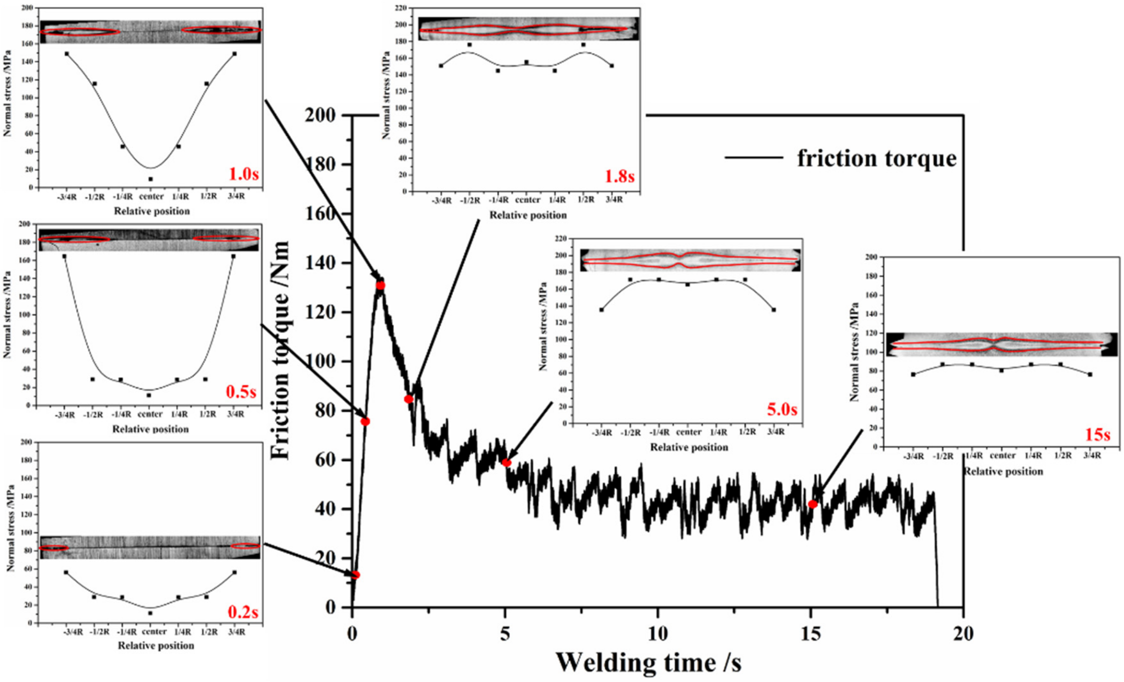


Fig 5. Jin Feng [27,28] Experimental results on the relationship between the pressure distribution at the SUS304 interface and the evolution of the plastic ring

3.2. Heat Flow Model

The term heat-pattern was originally used to describe the outline of the microstructure change area (including the weld nugget zone and the heat affected zone) in the friction welded joint. In essence, it depicts the expansion process of the plastic ring core until it completely covers the friction interface and steadily extrudes (forming a flash), and finally presents the morphology of the plasticized metal at the joint interface. The introduction of this concept actually highlights the key role of process parameters in the evolution of interface morphology. The difference in morphology shown by different heat flow modes reveals the non-uniformity characteristics of the radial microstructure and mechanical properties of the joints.

Crossland [29] divided the heat flow mode of the joint into two classical types: 'scissors' and ' lens ' for the first time. Although in subsequent studies, scholars such as Satyanarayana [30], Udayakumar [31] and Ajith [32] have also touched on the heat flow model, these studies have not explored and expanded it in depth.

Li [17] also conducted a simple study on the heat flow mode of 20 # low carbon steel. Fig.6 clearly show that the heat flow mode gradually changes from ' scissors ' to ' disc ' with the increase of rotational speed.

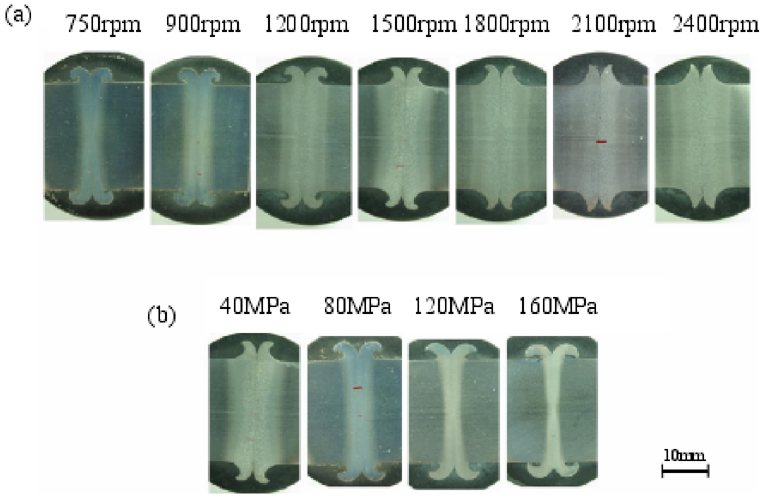


Fig 6. Experimental results of Li [17] on the heat flow model

Li [33,34] systematically classified and characterized the heat flow patterns of aluminum alloys under different rotational speeds. The results are shown in Fig.7. With the increase of rotational speed, the heat flow mode of aluminum alloy gradually shows the characteristics of ' scissors shape ', ' straight line shape ' and ' lens shape '.

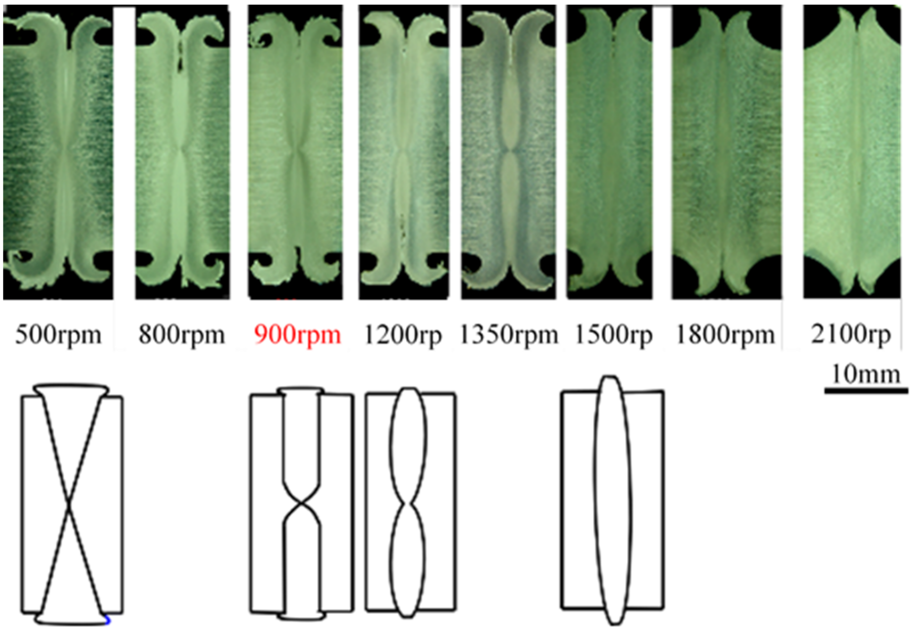


Fig 7. Experimental results of Li [33-34] on the heat flow model

Jin [27,28] conducted friction welding experiments on materials with different red hardness, including SUS304 stainless steel, GH2132 and GH4169, to deeply explore the joint heat flow modes of various materials in the friction welding process and the influence of different heat flow modes on the joint performance. The experimental results show that the heat flow mode of SUS304 stainless steel is less affected by the rotational speed, and its morphology is always maintained as a ' lens shape '. However, the GH2132 material exhibits a specific speed threshold of 900 rpm. When the rotational speed exceeds this threshold, the heat flow mode of the material changes significantly, from the original ' lens shape ' to the ' straight line shape '. In addition, after GH4169 material exceeds its critical speed, its heat flow mode changes from ' lens shape ' to ' spindle shape '. It is pointed out that although the existence of the friction line has no significant effect on the strength of the joint, it significantly weakens the plastic properties of the joint in the relevant region and leads to an increase in the inhomogeneity of the joint elongation distribution. These research results not only deepen our understanding of the change of heat flow mode of different materials in friction welding, but also provide valuable reference for the optimization of friction welding process parameters.

4. SUMMARY

In this paper, through the review of the research status of the interface evolution law of non-magnetic steel continuous drive friction welding, it is found that at present, the research on the interface evolution of non-magnetic steel materials is still in its infancy, especially for the special case where the plastic ring is not fully expanded, lack of targeted discussion. At the same time, the deep exploration of the microstructure evolution process and the internal grain characteristics during the formation of the heat flow mode of the non-magnetic steel is also relatively scarce. In view of the fact that the heat flow mode is essentially derived from the evolution of the plastic ring, it is of decisive significance to reveal the formation mechanism of the heat flow mode of the non-magnetic steel in combination with the plastic ring expansion mechanism.

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